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DESIGN OF 50,000G ACCELEROMETER CALIBRATION SYSTEM

Prepared by

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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The design, analysis and selection of the implemented system from alternate systems is discussed. The full details of the electrical and mechanical components are given. Included in the appendices are the manual for installation and maintenance and the operating procedures.

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1. ANALYSIS OF DESIGN REQUIREMENTS

At the present time, most accelerometers are calibrated on a vibrator or on a centrifuge at low g's, a practice that assumes linearity of the accelerometers up to their operating range, which may be several orders of magnitude above the calibration level. Various impact methods of producing high accelerations are available, but it is difficult to deliver accelerations in the 10,000g to 100,000g range and obtain accelerometer responses suitable for calibration purposes. Figure 1[1] illustrates the basic problem. If impact duration t_1 is shorter than the fundamental period of vibration, T, of the accelerometer, as in the left hand example of Figure 1, the accelerometer response consists essentially of "ringing" at its natural period with a considerable difference between the peak input acceleration and the peak response of the accelerometer. The other two examples in Figure 1 are with $t_1/T = 2.96$ and $t_1/T = 4.91$. In each case the accelerometer's ringing amplitude (undamped) is a much smaller fraction of the peak input acceleration. To account for the effects of total impact duration, the following design requirement is selected:

$$t_1 \geqq 3T \tag{1}$$

There are other characteristics of the g-time input that can also produce undesirable accelerometer responses, particularly rise time of the pulse. Zero-rise-time pulses like the square wave produce high amplitude ringing with an amplification factor of 2, as shown in Figure 2. A triangular pulse with zero rise time (the $t_p/t_1 = 0$ curve of Figure 3) will also produce high amplification factors. However, when the buildup time as a fraction of total duration is ½ or more, as shown in Figure 3, the amplification factors at $t_1/T \cong 3\text{-}4$ approach 1.0. The ideal combinations of t_p/t_1 and t_1/T are obtained when $(t_1/T) \times (t_p/t_1) = 2$, or:

$$t_p = 2T \tag{2}$$

Since both Eqs. (1) and (2) are related to the accelerometer's natural period, it is evident that the calibrator must either have the capability of varying its impact duration or its utility will be limited to accelerometers with a narrow range of natural periods. Fortunately, accelerometer natural

1. M. Kornhauser, "Structural Effects of Impact," Spartan Books, 1964.

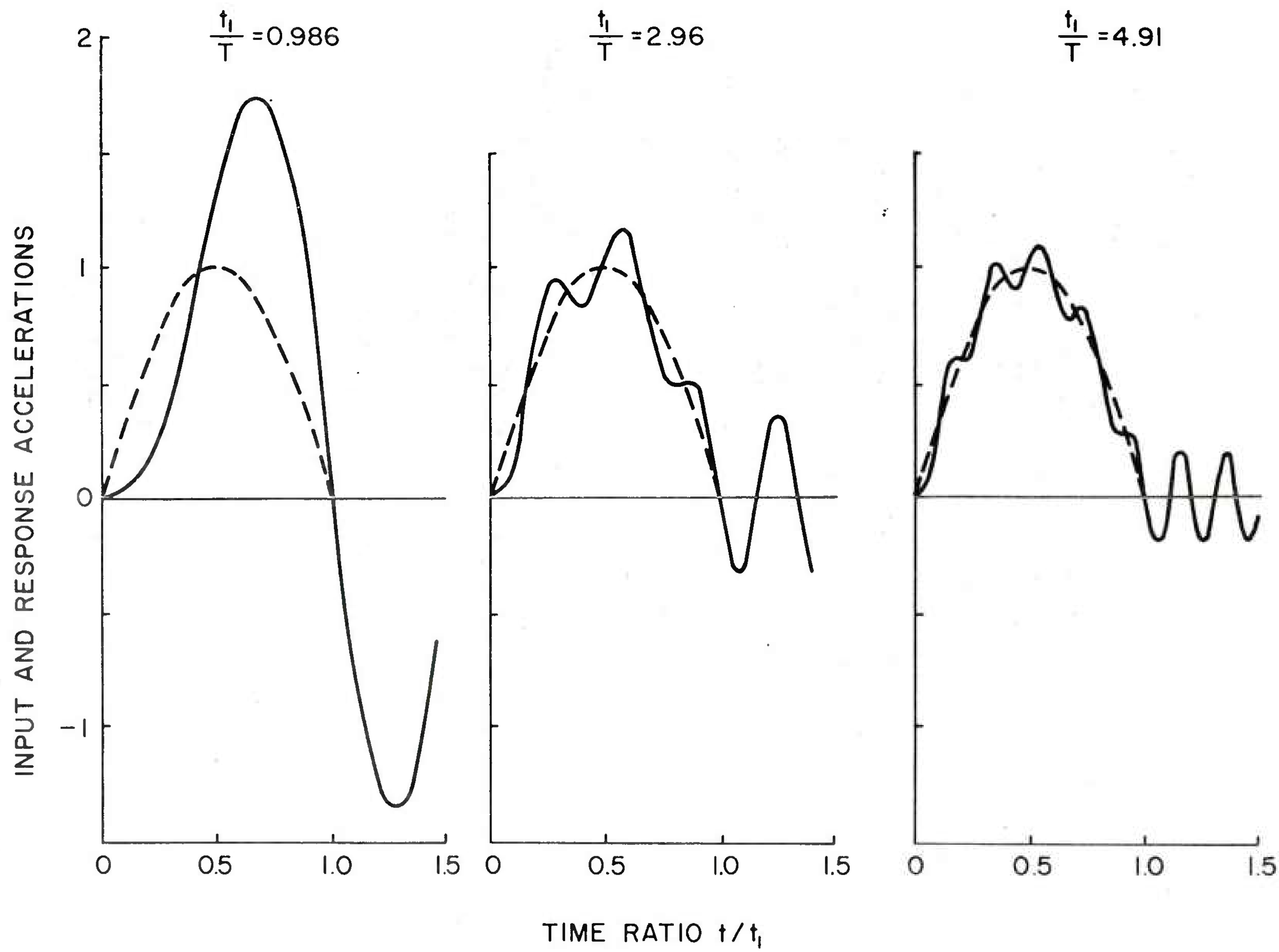

Figure 1. Responses to Half-Sine Inputs

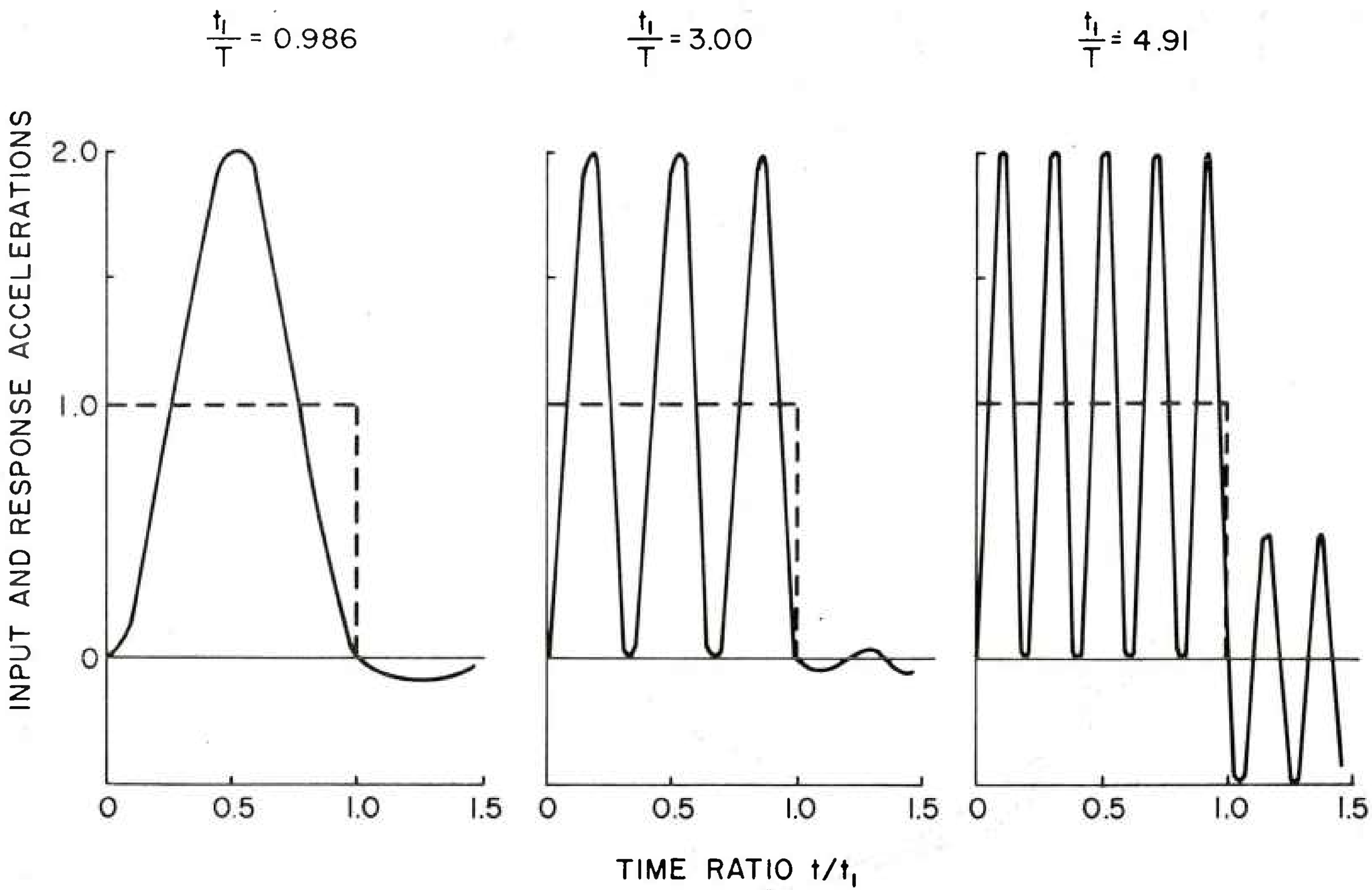

Figure 2. Responses to Square Wave Inputs

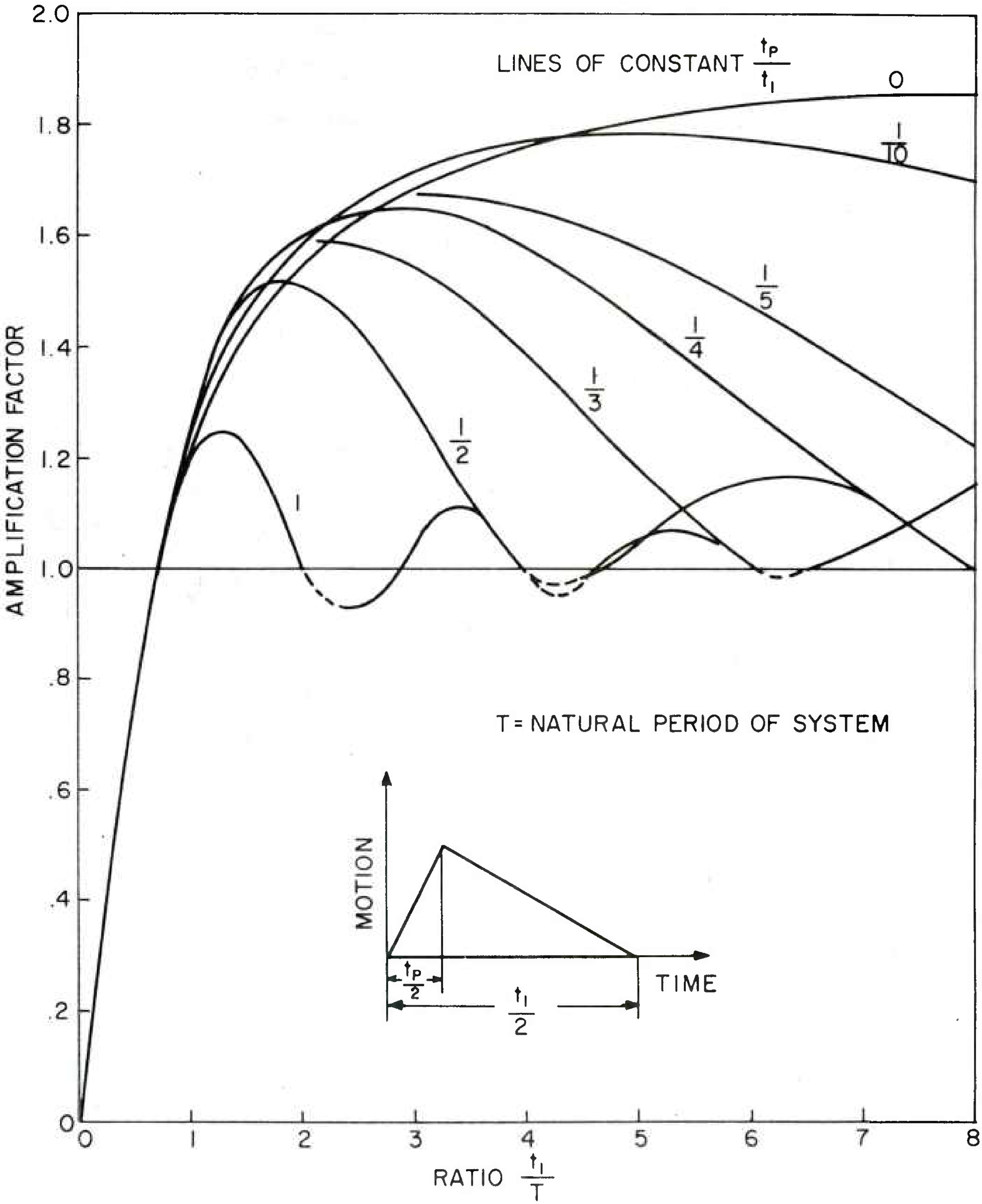

Figure 3. Effects of Buildup Time on Amplification Factor

frequencies and g-levels are correlated closely. Table 1, for example, lists several Columbia Research Laboratories high-g accelerometer frequencies and peak g's. Also given in Table 1 are impact durations t_1 using the minimum t_1/T according to Eq. (1). The requirement on impact duration would be $\geqq$ 120 microseconds if the calibrator were designed to accommodate all the accelerometers listed in Table 1.

There is a practical consideration involved in impact testing, that the accelerometer must be recovered safely after having been accelerated by the input pulse. For example, the velocity developed by a 50,000g pulse with a duration of 120 microseconds is $50{,}000(120\times10^{-6})(9.81) = 59$ m/s. Since it has been found in practice that velocities above about 30 m/s are increasingly difficult to handle safely, the desire to employ the longest possible duration must be tempered somewhat. Accordingly, the following requirement on impact duration has been adopted:

$$t_1 \geqq 90 \text{ microseconds} \qquad (3)$$

Note that a 90 microsecond calibrator would be suitable for all the accelerometers in Table 1 except for the 10,000g accelerometers. The requirement expressed by Eq. (3) is therefore seen to afford a fairly wide latitude in the range of accelerometers that could be tested by the calibrator, but it is also clear that not all accelerometers are included in this category.

Measurement of the input amplitude is an obvious requirement, but its method of accomplishment is not obvious in the absence of good "standard" accelerometers that have already been calibrated to 50,000g. Velocity measurement is much easier to accomplish, however, either directly with a velocity sensor or by using gravity as the primary standard as, for example, with a pendulum with a swing height determined by initial velocity and by the deceleration of gravity. Adopting the velocity measurement approach as a design requirement has the following implications:

(1) Until some "standard" accelerometers have been calibrated it will be necessary to record the test accelerometer's output, obtain the area under its output vs. time record, and equate the integral of $\ddot{x}dt$ to the measured velocity. The calibration constant, volts/g, will therefore consist of an integrated constant that will not be accurate at all g-levels if the accelerometer is non-linear.

(2) After a good "standard" accelerometer has been found with an output constant that is truly constant at different excitation levels, this accelerometer may be used for purposes of calibrating other accelerometers. When this kind of calibration is done, a single test will permit com-

Table 1. High G Accelerometers by Columbia Research Laboratories, Inc.*

	Ultra-High Sensit.			High Cap.		Miniature		Hi-G
Model	302-6	302-7	302-9	200-1	200-3	504-1	504-3	383
Peak G	10,000	40,000	40,000	10,000	40,000	40,000	40,000	20,000
f, kHz	25	35	50	25	50	50	60	80
Wt., g	35	23	21	16	10	12	10	8
Min. t_1, microsec.	120	90	60	120	60	60	50	13

*Extracted from the 1974 Catalog of Columbia Research Laboratories, Inc., Woodlyn, PA.

parison of the accelerometer's output with the standard, point-by-point, at all the acceleration levels delivered by the calibrator in that impact.

Implicit in the above discussion is the assumption that the calibrator's g-time outputs will not be known accurately until <u>it</u> has been calibrated. It is possible to design calibration systems with <u>peak</u> outputs that can be predicted accurately as, for example, if an air gun is used as the accelerator and the air pressure is measured at the time of release of the piston on which the accelerometer is mounted. However, the entire g-time history will not be known, and only a test accelerometer's peak output could be calibrated by a single test. It is therefore necessary to perform a complete calibration of the calibrator at all acceleration levels. Afterwards, it does not really matter if the calibrator's calibration curves are used as the standard for purposes of calibrating accelerometers, or if a "standard" accelerometer is used for that purpose.

2. SELECTION OF IMPLEMENTATION METHOD

A variety of methods of implementing the calibrator requirements have been considered, and the following have been rejected early in the process of evaluation:

(1) Air guns - Too expensive

(2) Bullet impacts - Usually too short-duration, but this adverse feature can be overcome by using a soft impact surface on the carriage. However, in the interests of developing a safe laboratory device, the use of explosives has been ruled out.

(3) Exploding foil - Duration too short.

(4) Electrohydraulics - Discharging a capacitor into an underwater gap can be made to produce a very intense, short-duration pressure pulse suitable for meeting the calibrator requirements. This approach is, however, a relatively inconvenient variation of the electromagnetic method which will be considered for detailed analysis.

(5) Low velocity impacts - The flat faced drop testers or other forms of impact device are rejected for reasons of lack of reproducibility from test to test. The round-nose impact surface approach is retained for further consideration.

Two prime candidates for implementation, round-nose impact devices and electromagnetic pulse devices, were considered in detail. Figure 4 contains plots of impact durations of steel balls on steel plates at low velocities. The required 90 microseconds duration can be obtained by ball diameters between 2.54 cm and 5.08 cm. If a mass larger than the solid

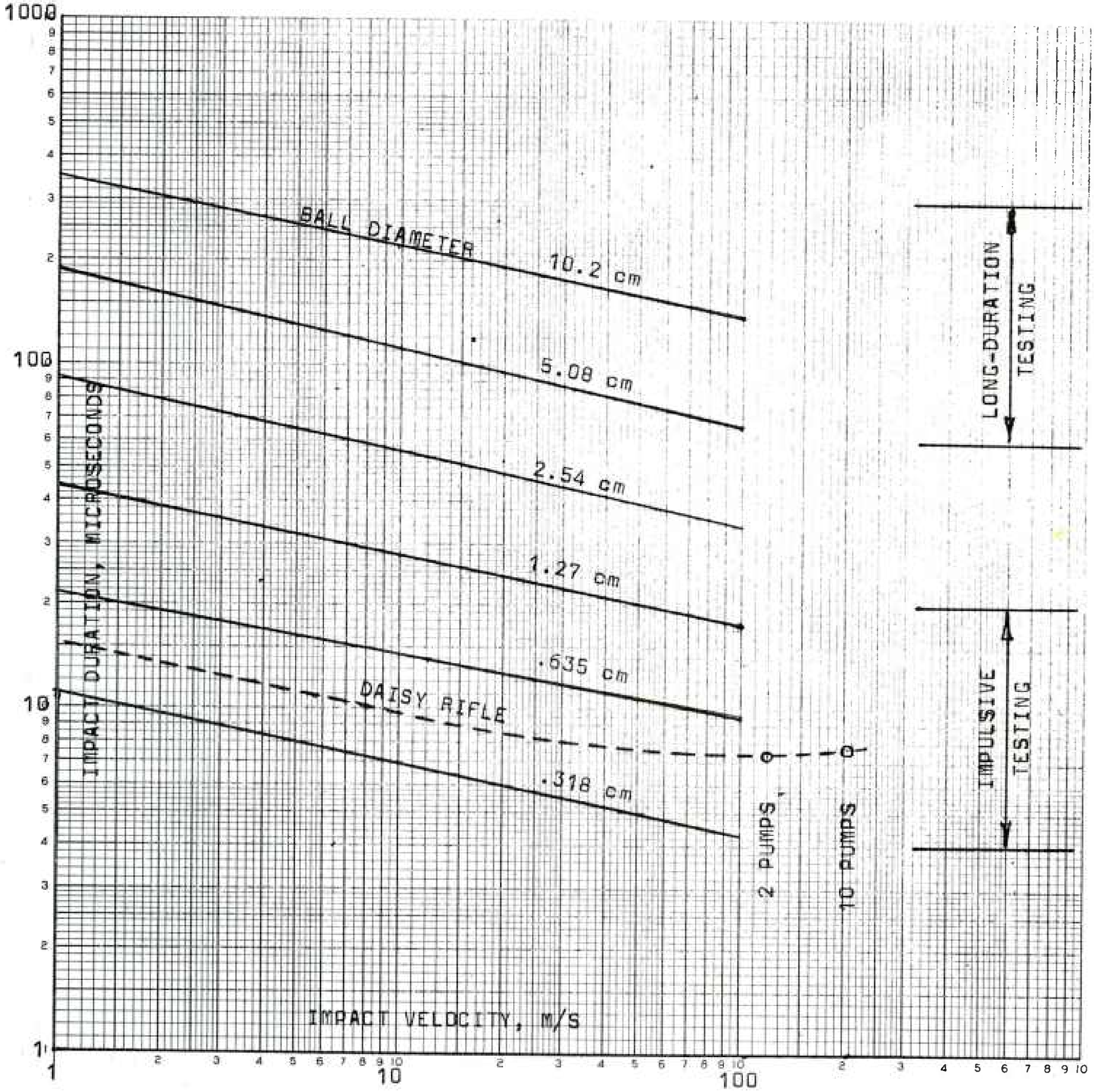

Figure 4. Steel Ball on Steel Plate

ball is required, however, these curves are not applicable. The case of a carriage with a nose diameter not equal to the carriage diameter has been analyzed[2] in detail. Also reported[2] are test performance data with a 5.08 cm diameter carriage (NOL Type 6A Drop Tester - Short Duration) with a 254 cm diameter round nose. It produced an impact duration of about 50 microseconds and a peak acceleration of 22,700 g at 3.45 m/s impact velocity. This carriage bounced with about 85 percent of its impact velocity. Since the bounce direction was not repeatable the carriage tended to strike its guides, thereby retarding the bounce velocity. It was therefore necessary to use high speed photography to measure the initial bounce velocity as the carriage left the anvil. In spite of the basic simplicity of this method and excellent correspondence between theoretical predictions and actual performance, it is the necessity for extreme precision in alignment and guidance that has been the determining factor in rejecting the round-nose impact approach. Table 2 presents some of the factors considered in comparing round-nose impact systems with electromagnetic systems. It was the repeatability issue that was the deciding factor in favor of the electromagnetic pulse method.

Figure 5 is an assembly drawing of the electromagnetic pulse calibration system. The coil assembly consists of a coil of copper strip conductor embedded in epoxy plastic, shown mounted on a reaction mass on the left, with the accelerometer and aluminum plate (carriage) on the right. When a capacitor is discharged into the coil, an intense electromagnetic field is created between the face of the coil and the aluminum plate, and the plate is accelerated away from the coil with a 50,000g acceleration and a pulse duration of 90-100 microseconds. Figure 6[3] shows a typical pressure-time pulse obtained with electromagnetic pulse equipment used for metal forming. These pulses are approximately the shape of a versed sine, with a buildup time somewhat less than half the duration of the pulse.

After the accelerometer has been accelerated, its carriage strikes buffers designed to provide a momentum exchange between the carriage and the pendulum with minimum bounce. Because of the large mass ratio, the pendulum will start its swing with a velocity of only about .6 m/s. The velocity sensor and the pendulum swing sensor provide independent measurements of the pendulum's velocity, from

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2. M. Kornhauser, "Potentialities of the Impact Machine for Producing High Accelerations," S.E.S.A. Proc., XIV, 2, 1955

3. E.J. Bruno, ed., "High Velocity Forming of Metals," American Society of Tool and Manufacturing Engineering, Dearborn, Mich. Revised Ed., 1968, Chap.5

Table 2. Comparison of Round-Nose Impact Systems with Electromagnetic System

	IMPACT SYSTEMS		ELECTROMAGNETIC
	GRAVITY, 4 Impacts	AIR OR SPRING PROP. 1 Impact	
PERFORMANCE			
(1) Repeatability, σ = 2% in 10	Guidance very difficult, a major problem	Guidance less difficult, but still a problem	Good
(2) Control of g and t	ΔV limited, Change R to vary t.	Change R to vary t	Vary V, L, C
(3) Alignment, Re-alignment	Necessary	Necessary	Easy
(4) Mat'l Expended in Testing	Impact Surfaces, Carriage	Impact Surfaces, Carriage	Carriage
OTHER FEATURES			
(1) Size (Approx.)	1.2m High 1.5m Long	.9m High 1.2m Long	.9m High 1.2m Long
(2) Develop. Req'd	Most	Average	Least
(3) Capital Cost	Least	+ $1,000	+ $2,000

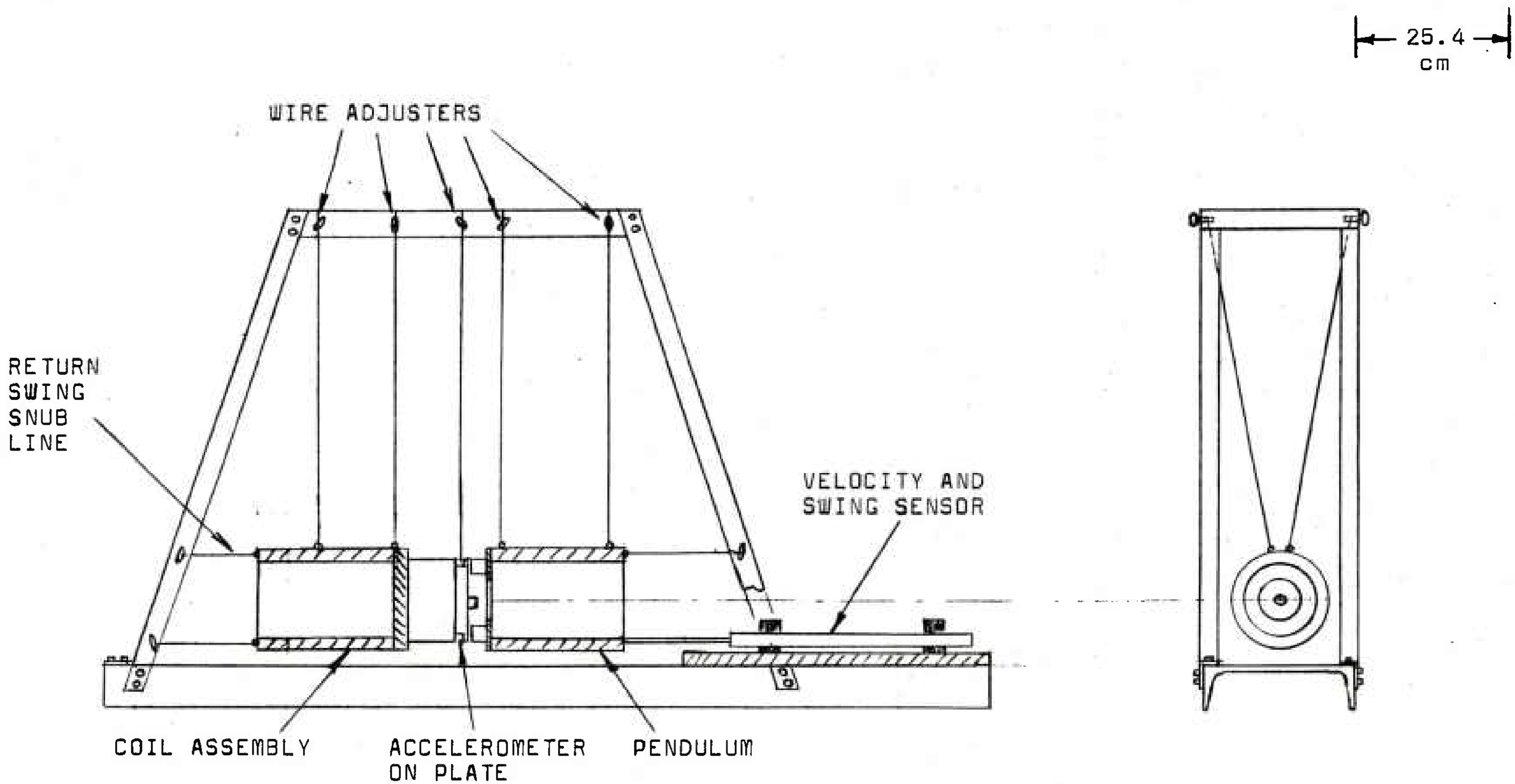

Figure 5. Assembly of Mechanical System

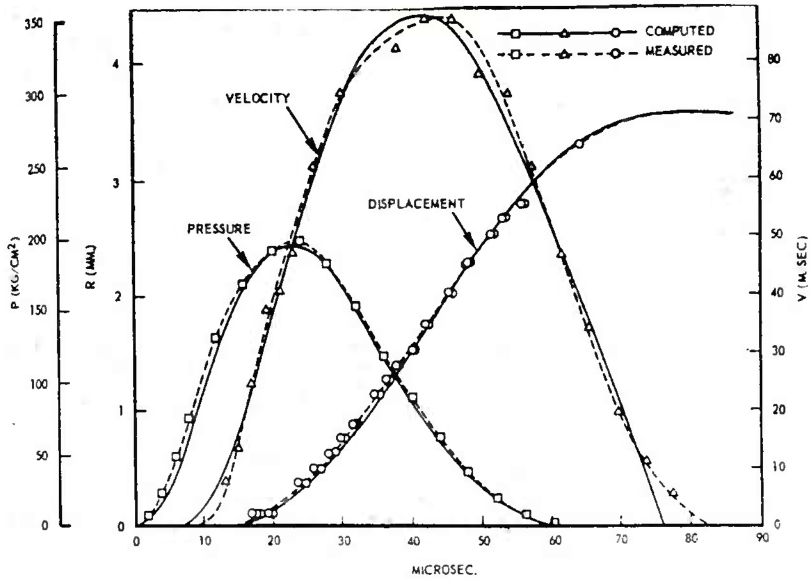

Fig. 6 Velocity, v, and displacement, r, of a Type 6061-O aluminum cylinder of 1.25 mm. wall thickness and 50.8 mm. outer diameter under a magnetic pressure, p..

which the accelerometer's velocity may be calculated. Design details of the electrical aspects and mechanical features are covered in the following sections of this report.

3. ELECTRICAL DESIGN

There are only a few critical elements in the electromagnetic pulse system, as follows:

(1) A power supply for charging the capacitor or capacitor bank.

(2) A capacitor or capacitor bank with sufficient capacitance and voltage to store the required energy, $\frac{1}{2}CV^2$. The capacitance also enters into the equation for pulse duration.

(3) A switch capable of dumping the capacitor's energy into the electromagnetic coil.

(4) An electromagnetic coil with enough turns and current-handling capacity to produce the field with high enough intensity, and high enough inductance to produce the required pulse duration.

3.1 Electromagnetic Coil

Flat coils, or "pancake" coils, with copper conductors in a spiral configuration, have been built for NASA in the early 1960's. Their performance characteristics have been reported[4,5]. Table 3 summarizes their design and performance features. Electromagnetic design of the coil will be based largely on the data given in Table 3.

The field produced by a pancake coil is far from uniform, as may be seen in Figure 7[4], and theoretical equations are not available for predicting the average magnetic pressure produced over the surface of the workpiece. A semi-empirical equation has been offered by M. Roberts of the Everson Electric Co., as follows:

$$B = .627NI\frac{\ln R_2/R_1}{R_2(1-R_1/R_2)} \tag{4}$$

where B is the field strength in gausses, N is the number of turns in the coil, I is the current in amperes, R_2 is the outer radius in centimeters and R_1 is the inner radius of the coil in centimeters. In order to evaluate the predictive accuracy of Eq. (4), it was applied to the design features given in Table 3 and comparisons were made between predicted and measured field strengths.

In Table 3 only the outer radius is given, but R_2/R_1 is required for Eq. (4). Fortunately, there are reports[5] on two additional pancake coils, one with $R_2/R_1 = 3.68$ and the other with $R_2/R_1 = 5.02$. The ratio $(\ln R_2/R_1)/(1-R_1/R_2)$ varies with R_2/R_1 as follows:

R_2/R_1	3	4	5	6
$(\ln R_2/R_1)/(1-R_1/R_2)$	1.65	1.85	2.01	2.15

Since Eq. (4) is not too sensitive to R_2/R_1 in the range from 3 to 5, a nominal value of $R_2/R_1 = 4$ will be used. Eq. (4) in the form $B = 1.161NI/R_2$ is applied to the data of Table 3, as given in Table 4.

Table 4 indicates that Eq. (4) predicts B from .83 to

4. NASA, "The Electromagnetic Hammer," NASA SP-5034, Dec. 1965.

5. M.C. Noland, et al, High-Velocity Metalworking, A Survey," NASA SP-5062, 1967, Chap. 2.

Table 3. Electromagnetic Coil Data

	Ref. 5			Ref. 4				
O.D. of Coil, cm	15.2	30.5	30.5	10	10	10	20	30
Number of Turns, N	17.4	17.2	17.5	5.7	10	10	6.7	6.5
Conductor Ht.or Coil Thick.()	1.27	1.27	1.91	(2.49)	(1.30)	(2.49)	(3.81)	(5.00)
Conductor Thickness, cm	.230	.635	.635					
Weight, kg	5.36	23.7	26.4	8.40	8.40	8.40	25.7	38.6
Wt. of Header, kg	11.8	11.8	11.8					
Inductance w/o contact, μh	12.2	23.7	21.2	.37	3.4	2.3	1.1	1.6
Inductance with contact, μh	5.4	6.7	7.6	.17	1.1	.77	.39	.56
t_p w/O contact, μsec	77.5	109.0	93.0	13	36	30	22	25 } 150 μf
t_p with contact, μsec	49.5	52.5	55.5	10	22	18	14	16
	At 10 kV, 12 kJ			At 10 kV, 7.5 kJ				
B w/o contact, kilogausses	39.55	13.65	10.29	60	70	70	30	25
B with contact, kilogausses	132.1	66.24	44.85	200	260	200	130	85
Max. I w/o contact, kA	44.30	31.74	33.59	170	65	75	105	90
Max. I with contact, kA	66.39	59.57	56.06	220	105	125	160	140

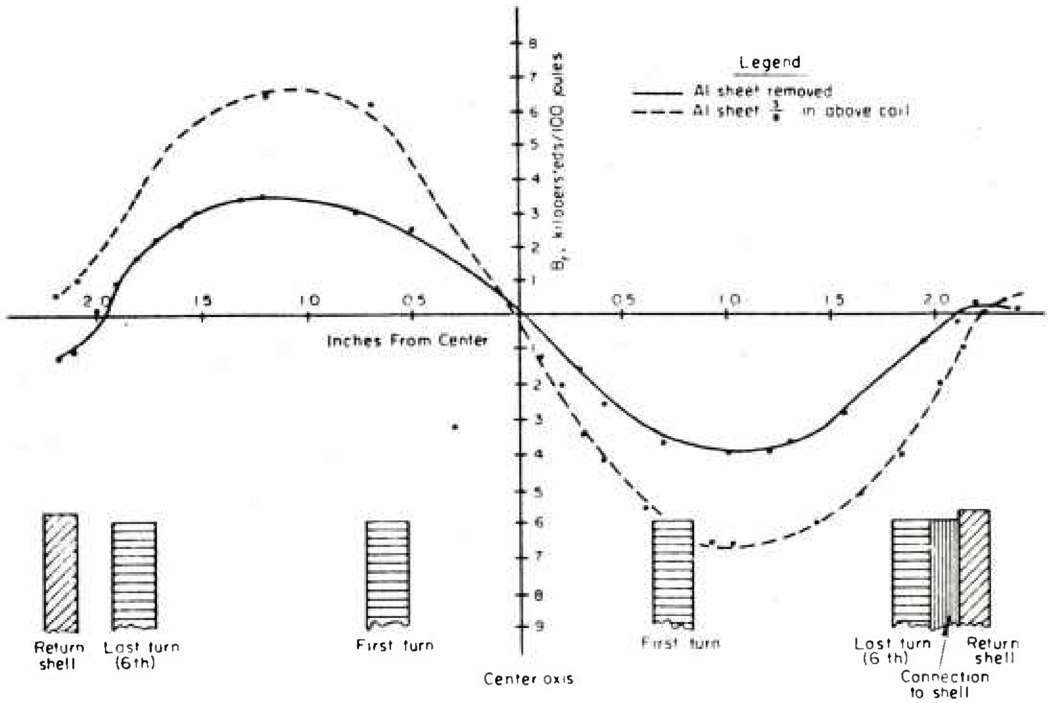

Figure 7a—Radial magnetic flux distribution for a 4-inch coil with and without the workpiece

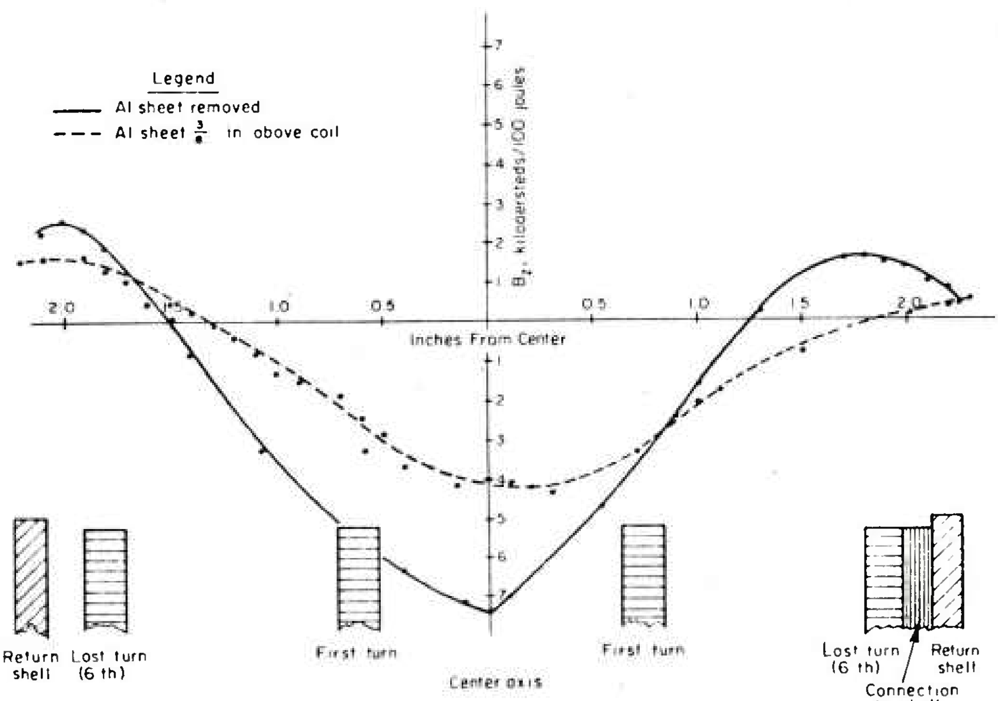

Figure 7b—Axial magnetic flux distribution for a 4-inch-diameter coil with and without the workpiece.

Table 4. Empirical Evaluation of Equation 4

COIL	1	2	3	4	5	6	7	8
R_2, cm	5.04	12.4	13.3	5.00	5.00	5.00	10.0	15.0
NI, kA	1155	1025	981	1254	1050	1250	1072	910
B, kilogauss	211	96	85.5	291	244	290	124	70.4
Measured B, kilogauss	132	66.2	44.9	200	260	200	130	85
Calc./Measured	1.60	1.45	1.90	1.46	.94	1.45	.95	.83

1.90 times B achieved in practice. Since it is advantageous to design a coil with a good margin of performance, Eq. (4) is modified by about a factor of 2.0 for use in design, as follows:

$$B = .30\frac{NI}{R_2}\,\frac{\ln R_2/R_1}{(1 - R_1/R_2)} \qquad (5)$$

To relate B to pressure:

$$P = 4B^2 \times 10^{-8}, \text{ atm.} \qquad (6)$$

This pressure is applied over the surface of the plate or carriage holding the accelerometer to be tested. If the pressure distribution (Figure 7, for example) does not match the mass distribution (and this kind of matching is difficult with the concentrated mass of the accelerometer at the center of the plate, even if one could rely on knowing the pressure distribution) there will be a tendency for the plate to vibrate and thereby drive the accelerometer in a forced vibration. For example, a 25 gram accelerometer with 1.59 cm base diameter is equivalent to a 4.55 cm thickness of aluminum. If this accelerometer is mounted on a low-frequency plate with thickness much less than 4.55 cm, for example .64 cm, the velocity distribution at the end of the relatively impulsive input will consist of a velocity gradient increasing from a low velocity at the center to a much higher velocity at the outer diameter. After the input pulse, the accelerometer would experience a forced vibration as the plate brought the accelerometer up to its own velocity.

In order to avoid a forced vibration input to the accelerometer, the plate's natural period must be designed to be short enough relative to the magnetic input pulse duration so that its vibrations are minimized. For free circular aluminum plates, Figure 8 gives the natural frequencies in the three lowest modes of vibration, according to equations[6] that agree well with experiment. With the plate loaded in its "umbrella mode", it would be expected to respond in the zero-nodal-diameter mode, with a natural frequency as follows:

$$f = 225\ h/R_2^2,\ \mathrm{kHz} \tag{7}$$

where h is the plate thickness in cm. For a ratio $t_1/T = 2$, with $t_1 = 100$ microseconds, natural period T is 50 microseconds and $f = 20$ kHz. Table 5 shows how thick the aluminum plate must be in order to obtain a natural frequency of 20 kHz, its weight, the peak pressure required to produce 50,000 g, the associated magnetic pressure, and NI from Eq. (5) with $R_2/R_1 = 4$.

Table 5. B for 20 kHz Aluminum Plates

R_2, cm	3.81	4.45	5.08	6.35	7.62
h for 20 kHz, cm	1.29	1.76	2.30	3.59	5.17
Plate Weight, kg	.163	.303	.516	1.26	2.61
Total Weight, kg	.188	.327	.541	1.28	2.64
P, atmospheres	173	236	308	481	693
B, kilogausses	65.8	76.8	87.7	110	132
NI, kA	445	605	790	1235	1778

The number of turns N affects B strongly according to Eq. (5), it is dependent on R_2 because of practical values of conductor thickness and insulation thickness, and it affects inductance L directly, as shown by Figure 9. Coil inductance appears to be relatively independent of coil diameter and of conductor cross section dimensions, but Figure 9 shows its dependence on N. Accordingly, the curve of Figure 9 will be

6. S. Timoshenko, "Vibration Problems in Engineering," 2nd Ed.; Van Nostrand, 1937, pp. 430, 431.

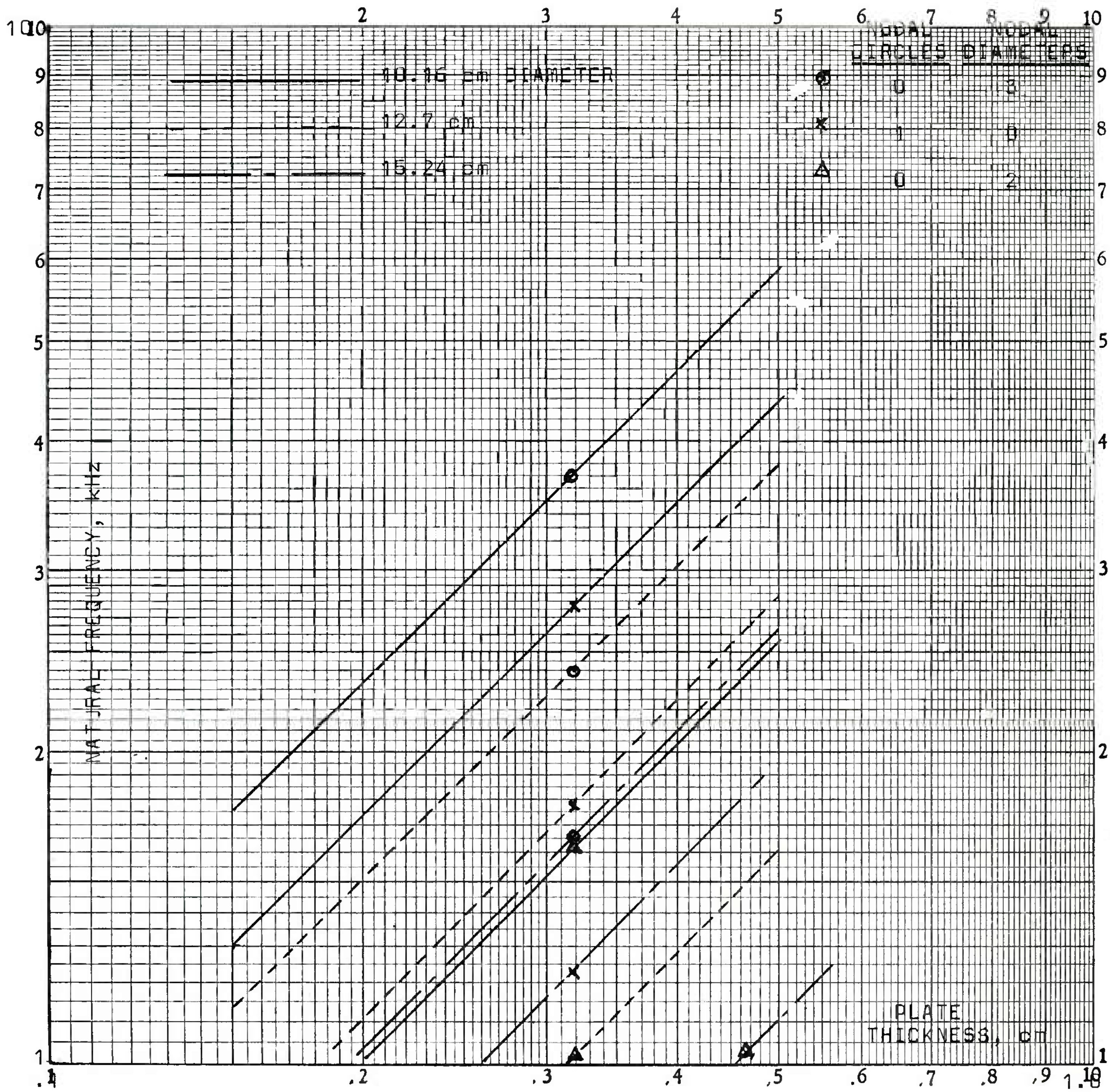

Figure 8. Natural Frequencies of Free Circular Aluminum Plates

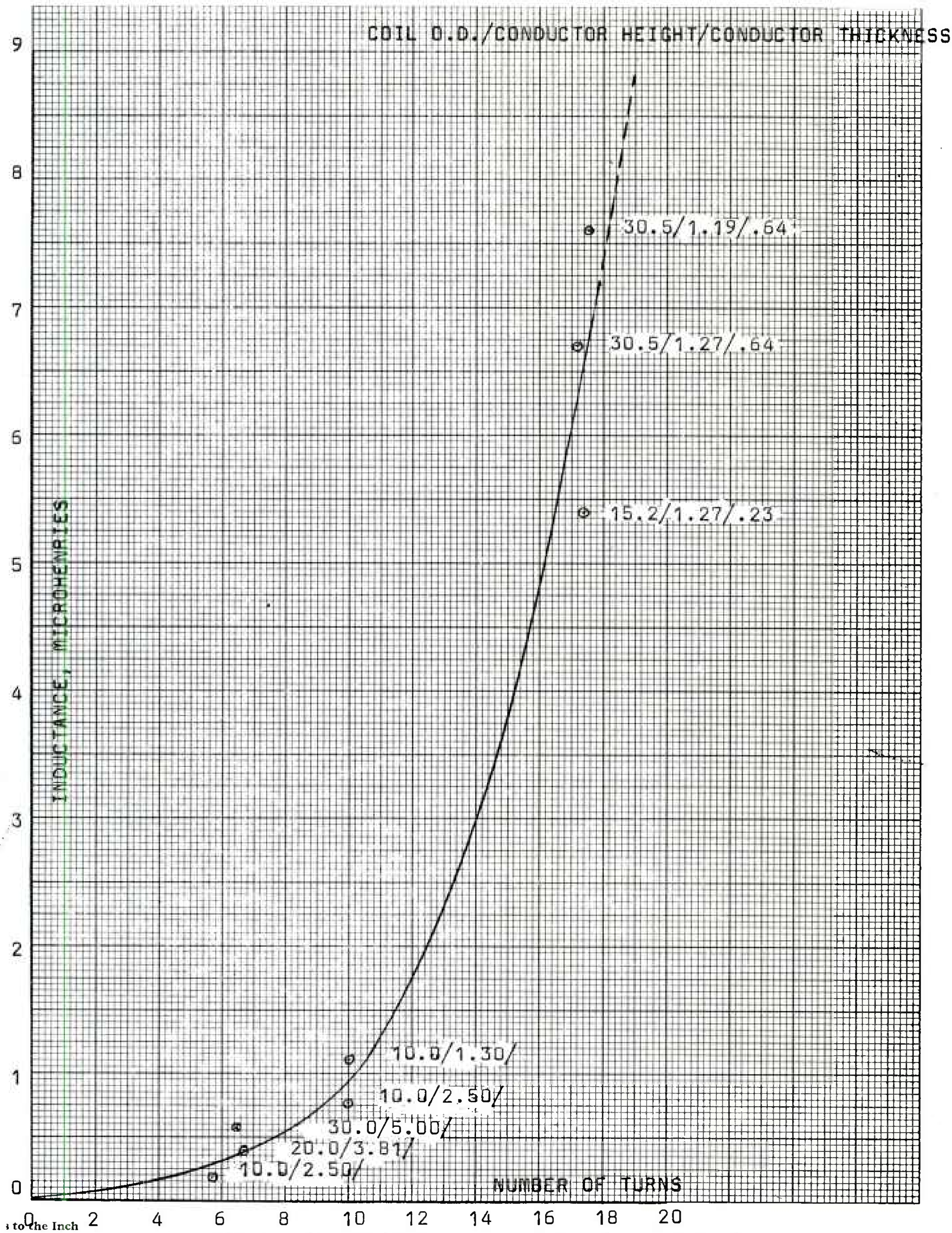

Figure 9. Coil Inductance vs. Number of Turns

used for predicting coil inductance, which generally consists of most of the inductance of the discharge circuit.

The number of turns that can be fitted into a coil of given diameter will be estimated on the basis of conductors .229 cm thick with insulation .076 cm thick, since this combination was used in several of NASA's successful coils. With $R_2/R_1 = 4$:

$$N = \tfrac{3}{4}R_2/.305 \tag{8}$$

For the coils presented in Table 5, Eq. (8) states the maximum number of turns and the minimum current, as given in Table 6. Also included in Table 6 are values of L taken from Figure 9.

Table 6. N, I, and L for 20 kHz Plates

R_2, cm	3.81	4.45	5.08	6.35	7.62
N from Eq. (8)	9.4	10.9	12.5	15.6	18.8
I=(NI)/N, kA	47.5	55.3	63.2	79.0	94.8
L, Fig. 9, μh	.80	1.25	2.00	4.40	8.60

The voltage and capacitance are related to L and I by the following equation for the under-damped circuit:

$$V = I(L/C)^{\frac{1}{2}} \tag{9}$$

Some Maxwell Laboratories, Inc. capacitors will now be considered for use with these coils, if their combinations of capacitance and peak voltage ratings are suitable. Taking I and L from Table 6 and combining them with C of each candidate Maxwell Laboratories capacitor, one may use Eq. (9) to find the voltage required. Table 7 contains the results of these calculations, and it also gives the peak voltage rating of the capacitor. Whenever the voltages exceed the capacitor's maximum rating they are circled, indicating that the capacitor is not suitable for that coil. Table 7 shows that only the 7.62 cm and 10.2 cm diameter coils have a good match with these Maxwell Laboratories capacitors.

Table 7. Matching Capacitors and Coils

Maxwell Capacitor		33004	33003	33002	33001	33501
C, microfarads		60	120	180	240	400
kV from Eq. (9)	R_2=3.81	5.48	3.88	3.17	2.74	2.12
	4.45	7.98	5.64	4.61	3.99	3.09
	5.08	11.5	8.16	6.66	5.77	4.47
	6.35	21.4	15.1	12.4	10.7	8.29
	7.62	35.9	25.4	20.7	15.0	13.9
kV Rating		10	7	6	5	5

Buildup time, t_p, for an under-damped circuit is as follows:

$$t_p = \tfrac{1}{2}\pi(LC)^{\frac{1}{2}} \qquad (10)$$

where t_p is in microseconds if L is in microhenries and C is in microfarads. Applying Eq. (10) to the non-circled combinations of Table 7:

Table 8. Buildup Times, Microseconds

R_2 \ Capacitor	33004	33003	33002	33001	33501
3.81	10.9	15.4	18.9	21.8	28.1
4.45	13.6	19.2	23.6	27.2	35.1
5.08	-	-	-	-	44.4

Of the combinations of coils and Maxwell capacitors matched in Table 8, only the 10.16 cm diameter coil and the 400 microfarad capacitor have a high enough LC to make t_p equal about half the t_1 requirement of Eq. (3). It is of course an alternative solution to use more than one capacitor to form a bank with higher capacitance. Using the capacitor bank approach, any of these candidate capacitors would be suitable for use with any of the coils, both from the standpoint of producing a high enough t_p and a low enough peak voltage. In the interests of economy, however, the 10.16 cm diameter coil is selected as the best size.

Some attempt to match the plate's mass distribution with the magnetic pressure distribution appears advisable, not only to minimize the non-uniformity of acceleration over the plate's surface that tends to force a vibration, but also to increase the plate's natural frequency at the same time. If a 2.54 cm thick aluminum plate is used (Table 5 gives 2.30 cm for the 20 kHz, 10.16 cm diameter plate), it would appear beneficial to decrease the plate's thickness to about .64 cm from R = 3.81 cm to R = 5.08 cm. The weight of the plate will also be reduced to .383 kg, so that higher accelerations may be obtained with the same electromagnetic system.

Figure 10 is a sketch of the coil assembly, very similar in design to a 10.16 cm coil[4] built for NASA and tested with a 240 microfarad capacitor bank to 14,000 joules without any visible signs of failure. The following procedure was given for the manufacture of this coil, using a thermal-setting epoxy resin with the following composition:

Wt., percent	
55.5	Epirez 5091 (Jones-Dabney Co.)
33.3	LP 3 (Thiokol Chemical)
11.2	Curing Agent "Z" (Shell Chemical)

(1) Wrap wire and BP 908-181 epoxy-impregnated glass-cloth strip, or equivalent, for 12.5 turns. Coil laminated as follows: first 3 turns with 3 laminates, next 6.5 turns with 1 laminate, and last 3 turns with 3 laminates.

(2) Apply Scotchweld EC 1386 adhesive (Minnesota Mining & Mfg. Co.) to both faces, filling voids.

(3) Oven cure for 1 hour at 450°K using pressure plates against each coil surface.

(4) Wrap coil completely using BP 908-181 (or equiv.) epoxy-impregnated glass cloth.

(5) Oven cure for 90 minutes at 436°K.

(6) Encapsulate coil using -100 epoxy resin (51% Epirez 5091, 43.8% LP 3, 5.2% Diethylenetriamine) and cure at room temperature.

(7) Cement aluminum plate to cured epoxy face using epoxy-resin adhesive (as in item 6 above) and cure at room temperature.

3.2 Capacitor

Circuits for electromagnetic metal forming tend to be under-damped. For critical damping, the following equation applies:

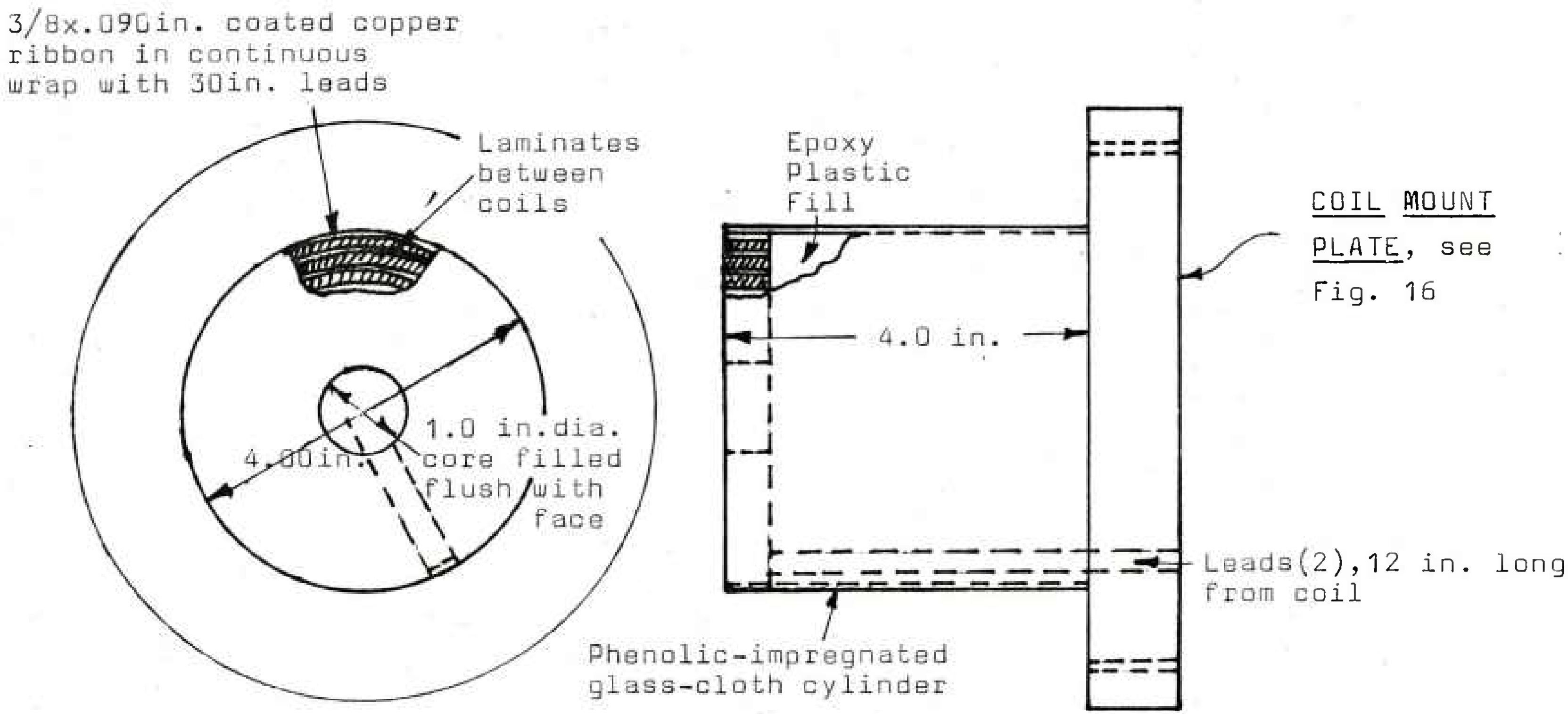

Figure 10. Coil Assembly

$$R = 2(L/C)^{\frac{1}{2}} \tag{11}$$

The 10.16 cm diameter coil with L = 2.00 microhenries, used with a 400 microfarad capacitor, would need a total circuit resistance of .14 ohms for critical damping. The resistance of the coil itself, with about 6 m of copper ribbon .23x.95 cm in cross-section is calculated to be only about .0045 ohms. With such a small circuit resistance, the discharge would be distinctly oscillatory and the first voltage reversal would be about 94 percent of the applied voltage, according to the following formula:

$$V_r/V = e^{-\frac{1}{2}\pi R(C/L)^{\frac{1}{2}}} \tag{12}$$

Fortunately, however, the circuit's effective resistance is largely due to the resistance coupled from the workpiece into the coil. For example, V_r/V is about 0.7 for one metal forming coil[4] and about 0.6 for another[3]. Figure 11, taken from Maxwell Laboratories Bulletin 301-1 (data sheet for Series C Pulse Discharge Capacitors) shows that voltage reversals can be expected to shorten the life of the capacitor. Figure 11 shows that the life expectancy of the capacitor would be lowered excessively if the coil resistance alone is considered, but good life can be anticipated with coils acting on metal workpieces.

Maxwell Bulletin 301-1 gives the following figures on characteristic life expectancy of the capacitors considered in Tables 7 and 8:

Capacitor	Cycles with 0-20% Voltage Reversal	Cycles with 80% Voltage Reversal
33001-33004	1×10^6	1×10^5
33501	2×10^5	1×10^4

These numbers are high enough even with high voltage reversals for a capacitor that discharges only once per test, when employed in the calibrator's electromagnetic circuit.

3.3 Switch

Various kinds of switches have been used with electromagnetic metal forming circuits including partially-evacuated gap switches, air-ionization gap switches, and crowbar ignitrons. At the voltage levels contemplated for the

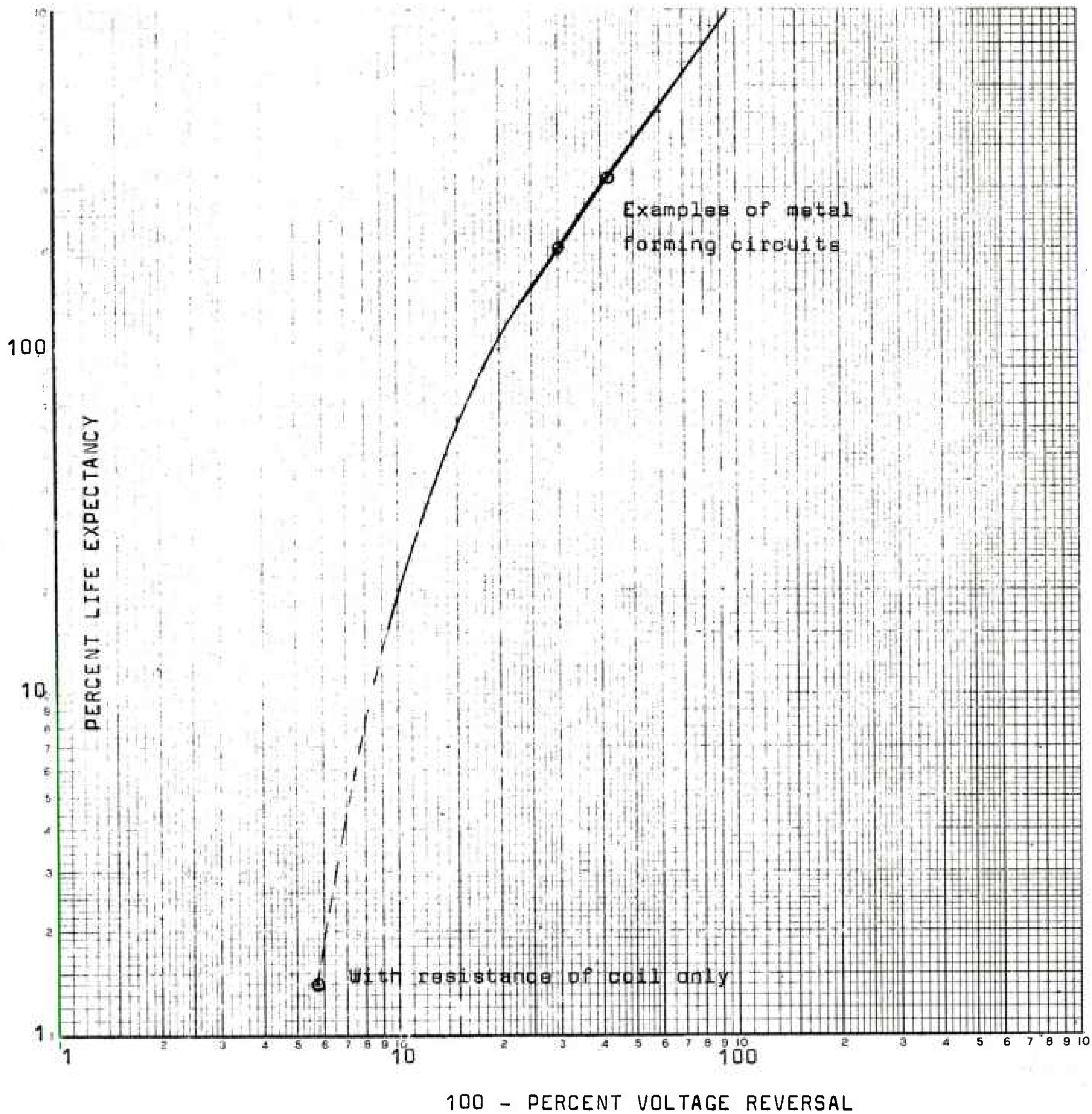

Figure 11. Life Expectancy vs. Voltage Reversal

calibrator there will be no need for an evacuated gap, and either a simple air gap switch or an ignitron switch would be appropriate.

Figure 12 gives spark gap distances vs. voltages for needles and for spheres with various diameters. At 5-10 kV, the spark gap distance is less than about .5 cm using spheres with any diameter less than about 2.5 cm. It is therefore planned to employ a solenoid-operated gap as follows:

(1) During the capacitor charging cycle, the spheres are held a distance of about 1 cm or more.

(2) When the capacitor has been charged to the desired voltage, the charging switch will be opened to prevent damage to the power supply.

(3) A solenoid will be actuated in order to move one sphere to within about 0.1 cm of the other, thus allowing the capacitor to discharge into the coil circuit.

It is difficult to predict at this time whether the circuit will be oscillatory to the extent that more than one pressure pulse will be delivered to the accelerometer. If this is found to occur to an objectionable extent, it may be necessary to use a crowbar ignitron switch that opens when the current drops to zero, thereby preventing oscillations.

3.4 <u>Safety</u>

All high voltage equipment including the power supply and the capacitor bank will be housed in a grounded steel enclosure. The following additional safety features are planned:

(1) Warning lights will indicate that more than 100 volts exists across the bank.

(2) The enclosure's access door will be fitted with an interlock for shorting the capacitor bank to ground.

(3) The charging switch will not function if the access door is open.

(4) The spark gap switch will not be accessible to operator contact during normal operation.

(5) The solenoid for operating the spark gap switch will be normally open. Power will be made available to the solenoid by a switch in series with the solenoid operating switch.

(6) The solenoid switch will be located at a station directly in front of the coil to prevent system function while personnel are mounting the accelerometer to be tested or are adjusting the instrumentation.

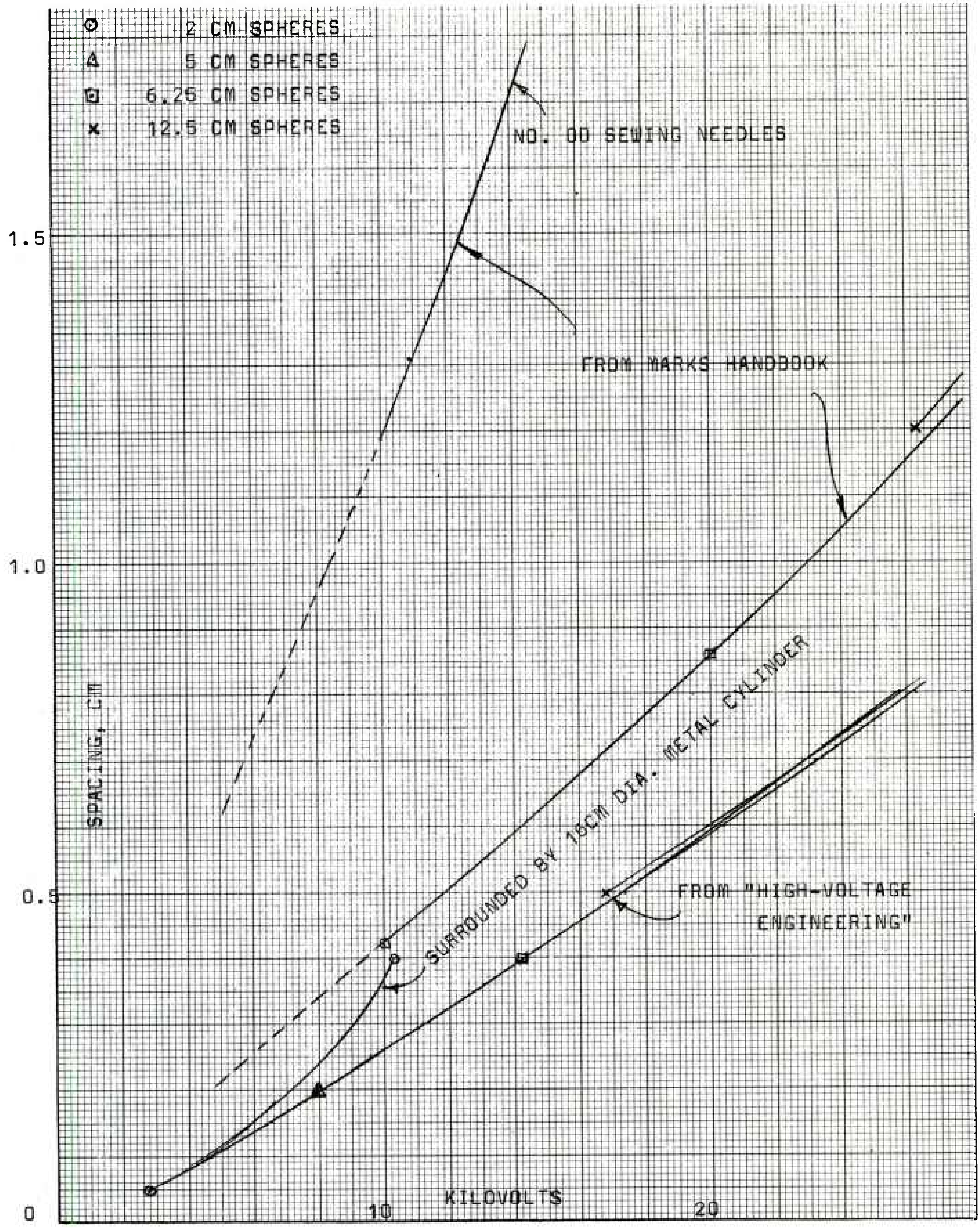

Figure 12. Spark Gap Distance vs. Voltage

4. MECHANICAL DESIGN

4.1 Pendulum

The accelerometer and mounting plate, weighing about .408 kg when a 25 gram accelerometer is being tested, will be accelerated by a pulse with a peak acceleration of 50,000g, a duration of about 100 microseconds, and a form factor of the order of .60. Since this acceleration pulse will produce a velocity of about 31 m/s, rather high decelerations will be required to stop the plate in a reasonable distance. The average decelerations necessary to bring the plate to rest from 31 m/s are given in Table 9.

Table 9. Stopping Distances and Reverse G's

Stopping Distance, cm	7.62	5.08	2.54	1.27
Average deceleration, g	621	932	1863	3727
Reverse g/50,000	.012	.019	.037	.075
Avg. Force, kg	253	380	760	1520

Although the plate could be brought to rest against some rigid barrier, it was decided to have the plate strike the cushioned surface of a pendulum. This arrangement prevents any high stopping forces from being delivered to the calibrator's framework. Further, the plate's velocity after undergoing a momentum exchange with the massive pendulum is reduced enough to make velocity measurements very easy, and also permit the pendulum's swing to serve as a velocity measurement. A pendulum with length L starting with velocity equal to mV/(M+m), where m is plate mass and M is pendulum mass, will swing to height H, as follows:

$$H = \left(\frac{m}{M+m}\right)^2 V^2/2g \qquad (13)$$

The horizontal swing x is as follows:

$$x^2 = H(2L-H) \qquad (14)$$

Eqs. (13) and (14) are plotted in Figure 13 for various lengths L. It is convenient physically to keep x and H as small as possible. However, in the interests of being able to use x as a velocity measurement, the larger x is made the smaller the percentage error made in this measurement. A

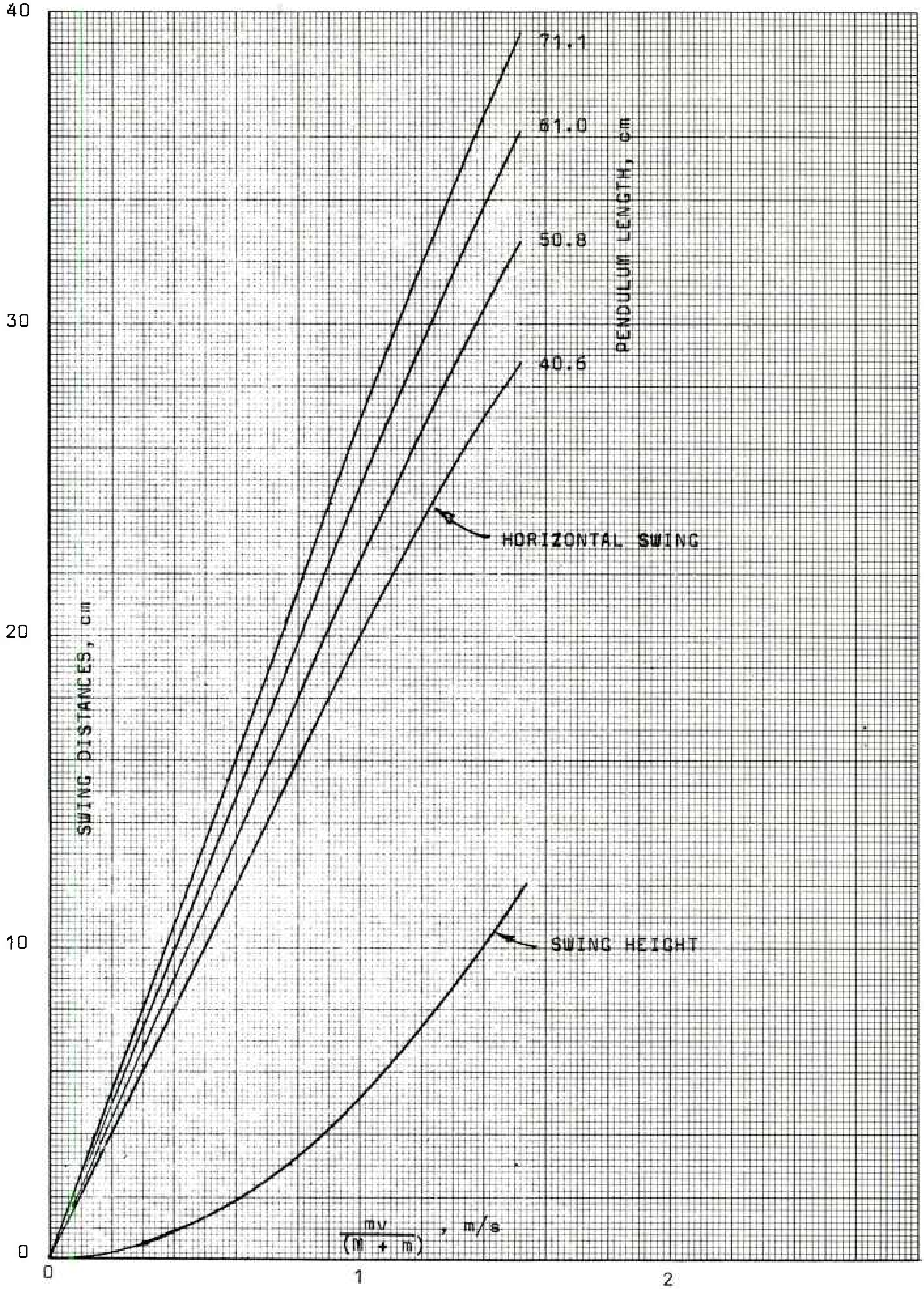

Figure 13. Pendulum Performance

reasonable compromise has been taken as x = 15 cm and pendulum velocity = .6 m/s, which leads to a swing height of about 2 cm. From the momentum exchange equation:

$$M = \left(\frac{31}{.6}\right)(.408) = 20 \text{ kg} \tag{15}$$

The coil can also be treated as a pendulum, with the double-pendulum configuration shown in Figure 5. If the coil weight is increased to about 20 kg by adding about 16 kg of weight to the coil itself (see Figure 10), it should theoretically swing the same amount as the pendulum. However, it is expected that the rigidity of the coaxial cable leading to the coil will interfere with the coil's swing enough to prevent its use in making meaningful measurements.

4.2 Accelerometer Recovery System

Various materials and concepts were studied for reducing the plate's 31 m/s velocity down to the pendulum's .6 m/s swing velocity. Several rubber and plastic buffers were found to have low enough dynamic moduli, in the 14 - 55 MPa range, but the percentages of energy return or bounce were not considered acceptable. Plastic foams [7,8] have eminently suitable properties but are not readily available. Balsa wood, on the other hand, has been found to absorb large amounts of energy softly with little bounce[9] and it can be purchased at any hobby shop. Accordingly, a bar of balsa wood with 2.54x2.54 cm cross-section was purchased, cut into 2.54 cm cubes and tested. Figure 14 is the deflection vs. force curve for the 2.54 cm cube of balsa loaded normal to the grain. It proved too stiff for this application when loaded parallel to the grain.

Figure 15 contains a curve of energy absorbed vs. deflection. Using the energy curve, it was possible to calculate the deflections and peak reverse g's that the catcher and accelerometer would experience, using various numbers of 2.54 cm cubes mounted on the face of the pendulum. With 3 cubes of balsa, the .408 kg plate will be subjected to a deceleration about .133 times the 50,000g acceleration. In practice the balsa cubes may be glued

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7. D.L. Daigle and J.O. Lonborg, "Evaluation of Certain Crushable Materials," JPL Technical Report 32-120, Jan. 13, 1961

8. F.J. Limbert and W.J. Persin, "Impact Testing of High-Density Semirigid Urethane Foam for Automotive Bumper Applications," SAE Paper 720132, Jan. 10-14, 1972

9. D. Bresie, "Practical Limits for Balsa Impact Limiters," NASA TN D-3175, Jan. 1966

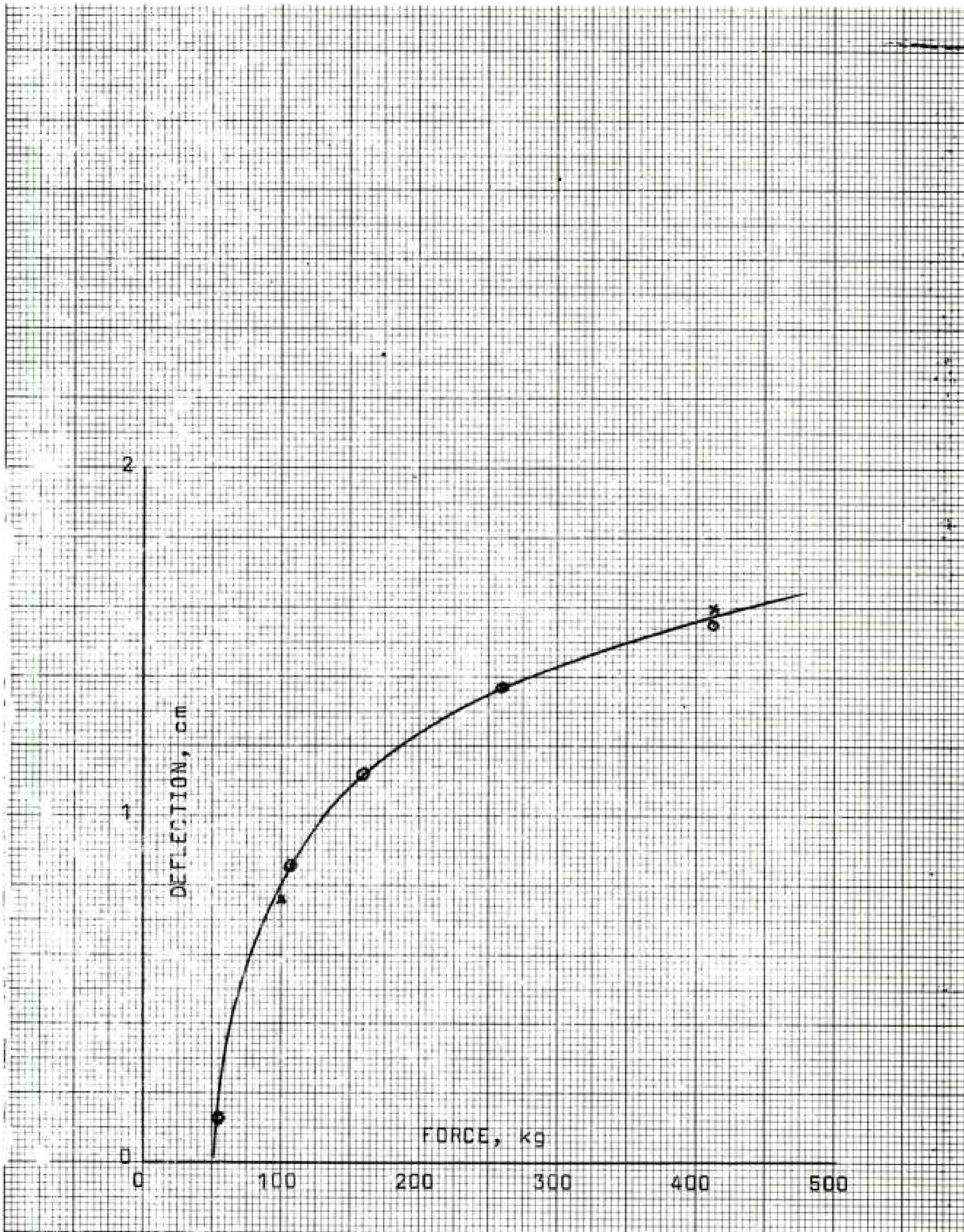


Figure 14. Deflection of 2.54 cm Cube of Balsa Loaded Normal to Grain

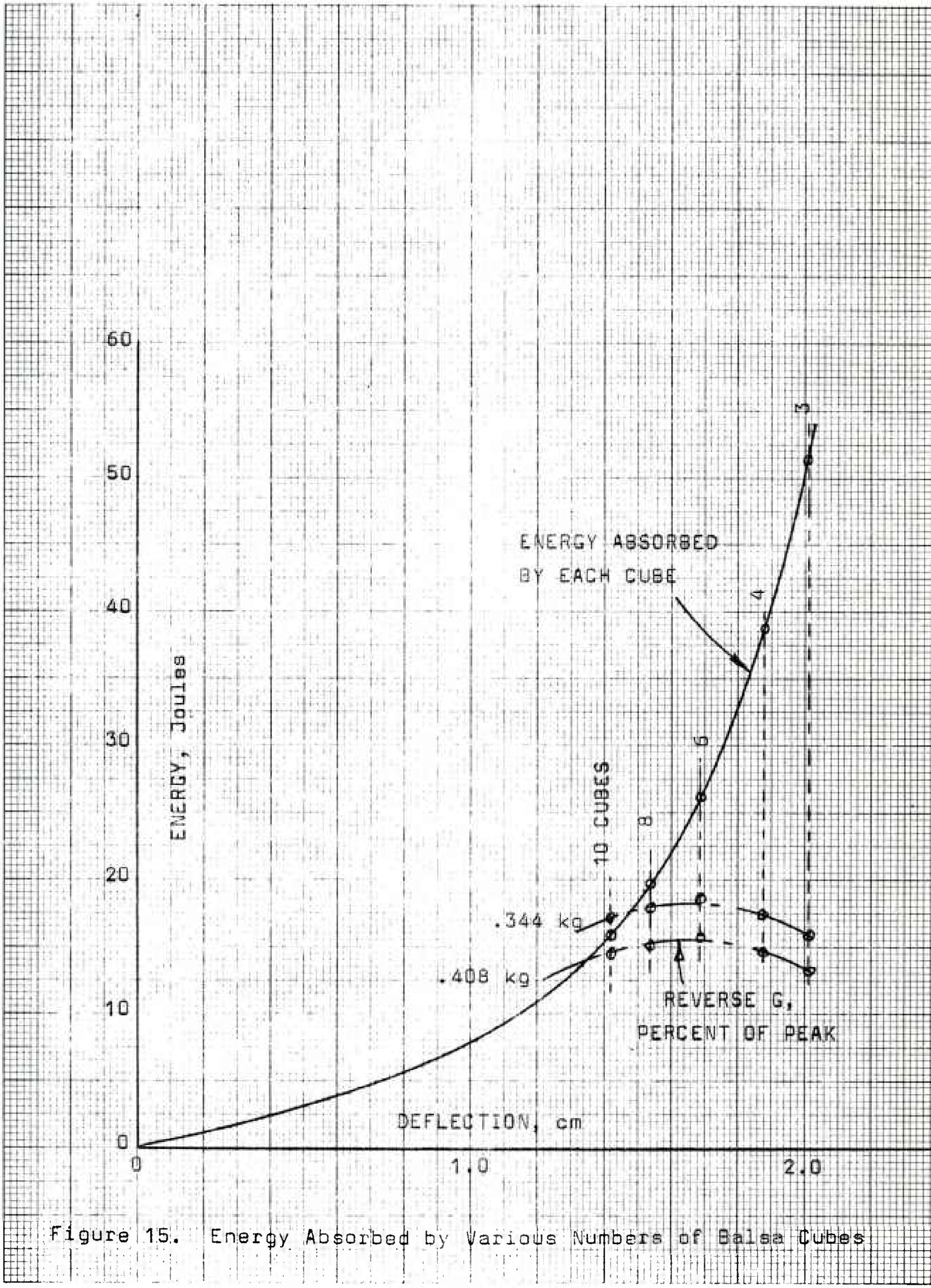


Figure 15. Energy Absorbed by Various Numbers of Balsa Cubes

or taped to the face of the pendulum. Figure 5 shows the plate suspended by wires for support in its initial position against the face of the coil, and for support after impact on the face of the pendulum.

4.3 Stress Analysis of Plate

The plate is loaded by an inertia load of 50,000g applied to 2.54 cm of aluminum (equivalent to an areal density of 689 Pa), which is equivalent to 34.5 MPa applied by the electromagnetic pulse. Since the plate is accelerating the 25 gram accelerometer with its areal density of 1234 Pa, this is equivalent to 61.7 MPa applied to the base of the accelerometer. Roark[10] gives the following equation for the maximum stress at the center of a plate loaded on one side by a constant pressure over area πr_1^2 and on the other side by a constant pressure over the entire area πr_2^2 (with Poisson's ratio taken as .30):

$$S_r = S_t = \frac{3(\pi r_1^2 p)(.30)}{2\pi h^2}\left[4.33 \log\frac{r_2}{r_1} + \frac{2.33}{4}\left(1-\frac{r_1^2}{r_2^2}\right)\right] \qquad (16)$$

where P is 61.7 MPa, h is .0254 m, r_2 is .0508 m, and r_1 is .00794 m. Entering these numbers into Eq. (16), S = 23.3 MPa. This stress is low enough so that any aluminum would be strong enough in a 2.54 cm thickness.

If the thickness of the plate is reduced to .635 cm from r = 3.81 cm to r = 5.08 cm, this outer ring behaves as though it is being subjected to a pressure almost 34.5 MPa higher than the rest of the plate because of its lower inertia. Treating this ring as a built-in plate, the following formula[10] applies:

$$S_r = \frac{3Pr_2^2}{4h^2}\left[\frac{17.33 \log\frac{r_2}{r_1} - 6.33 + 2.33\frac{r_1^4}{r_2^4} + 4\frac{r_1^2}{r_2^2}}{4.33 + 2.33\, r_1^2/r_2^2}\right] \qquad (17)$$

Applying P = 34.5 MPa, r_2= 5.08 cm, h = .635 cm, r_1= 3.81 cm to Eq. (17), S_r is calculated to be 482 MPa. The actual stress will be lower for the following two reasons:

10. R.J. Roark, "Formulas for Stress and Strain McGraw-Hill, 4th Ed., 1965

(1) The outer ring has some inertia by virtue of its .635 cm thickness, and the effective pressure should be of the order of $\frac{3}{4}(34.5)$ rather than the 34.5 MPa used in the calculation. This correction would reduce the maximum stress to about 361 MPa.

(2) The magnetic pressure distribution for a pancake coil (see Figure 7) should be quite a bit lower at the outer radius than at the center.

Despite these mitigating factors, a strong aluminum will be used for the plate; either 2024-T81,T851 with a yield strength of 414 MPa or 2024-T861 with a yield strength of 455 MPa.

Figure 16 contains drawings of some of the major mechanical parts of the coil, the pendulum, and the accelerometer mounting plate. Other mechanical parts shown in Figure 5 such as the angle iron framework, the massive channel to support the mechanical assembly (a 25.4 cm steel channel weighing approximately 29.8 kg/m), and other less critical components will be detailed as fabrication proceeds.

5. INSTRUMENTATION

In Figure 5 a velocity and swing sensor is shown resting against the rear of the pendulum. The sensor selected for this purpose is a Schaevitz Engineering velocity transducer 7L6VT-Z. The probe or core is a .635 cm diameter permanent magnet whose motion produces a voltage, as follows:

With Alnico V Magnet = 200 mV/in./sec.

With Non-Breakable Magnet = 80 mV/in./sec.

Since this is a self-generating device, no external excitation voltage will be required. Its output will be recorded by a digital peak reading voltmeter, calibrated to read the pendulum's velocity directly in m/s.

Because of the 1.91 cm vertical motion of the pendulum the probe will not be attached rigidly to the pendulum. Instead its end will be placed in contact with the rear of the pendulum and vertical sliding will occur as the pendulum swings. Two readings will be made:

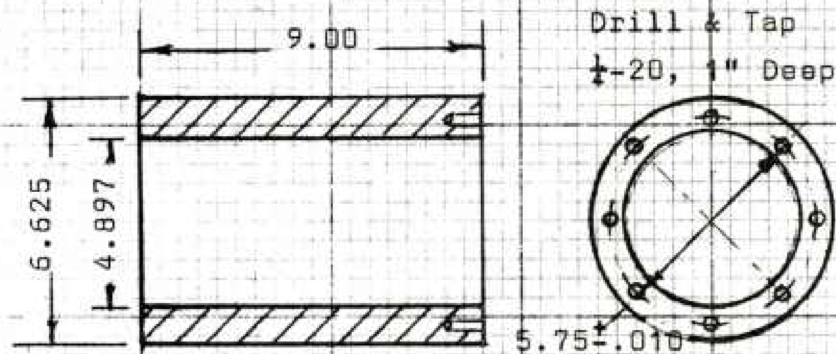
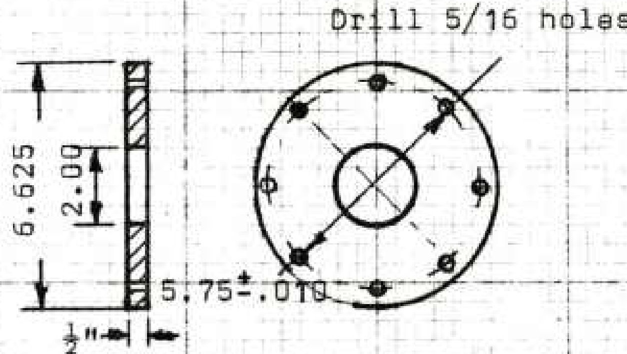
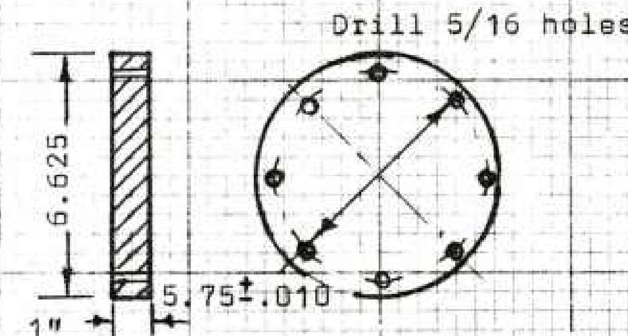
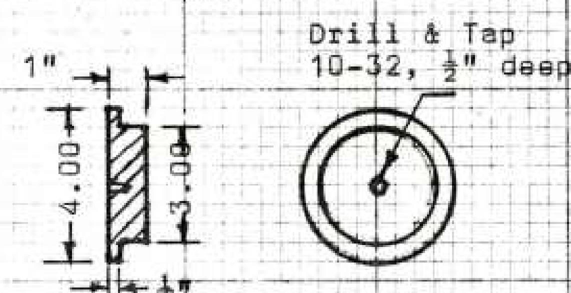
PART	DRAWING	MATERIAL
MASS (2 REQ'D)		Fabricate from 6-inch double extra strong steel pipe, 53.1 lb/ft.
SOFT PAD PLATE		Mild Steel
COIL MOUNT PLATE		Aluminum 2024-T861 or equiv. 60,000 psi yield req'd.
ACCELEROMETER PLATE		Ditto

Figure 16. Miscellaneous Parts Drawings

(1) Peak velocity of the pendulum, which occurs immediately after impact by the accelerometer plate.

(2) Maximum horizontal travel of the pendulum and sensor core, measured directly by taking the difference in initial and final positions of the core. Eqs. (13) and (14) will be used to calculate the pendulum's velocity, and this independently-measured velocity will serve to check the velocity sensor's reading above.

To obtain the accelerometer's velocity, it will be necessary to obtain the weight of the plate+accelerometer, w, and the pendulum weight W. The relationship of accelerometer velocity V to pendulum velocity v is as follows:

$$V/v = (W+w)/w \qquad (18)$$

As an alternate approach, the probe could be placed directly against the top of the accelerometer to read the accelerometer's velocity directly. The probe's 53 grams added to the .408 gram weight of the plate will not reduce the calibrator's capacity unduly, but it is quite possible that inaccurate readings would be caused by the probe bouncing off the accelerometer's surface. The high-g environment of the accelerometer, 50000 g and 31 m/s, is much more difficult to deal with than the lower-g environment of the pendulum (6650 g and .61 m/s).

None of the velocity measurements made above are necessary if a well-calibrated "standard" accelerometer is tested at the same time as the accelerometer to be calibrated, and their outputs compared directly. In the absence of such a standard, however, the test accelerometer's output must be recorded and the integral of the voltage-time record compared with velocity in order to obtain the accelerometer's mV/g constant. The voltage vs. time output of the accelerometer is recorded and the area under the curve obtained by numerical integration or by planimeter. In addition, some of the newer recording systems such as Nicolet and Biomation have features that permit easy integration.

Note that the accelerometer's constant obtained from a single test record is an average value for the range of accelerations experienced in that particular test. If the accelerometer is non-linear, a second test at a higher or lower peak acceleration could yield a different "constant". Accordingly, it is recommended that tests are run at several levels leading up to 50,000 g as a means of determining the linearity of the accelerometer.

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5. M.C. Noland, et al, "High-Velocity Metalworking, A Survey," NASA SP-5062, (1967) Chap. 2.

6. S. Timoshenko, "Vibration Problems in Engineering," 2nd Ed., Van Nostrand, (1937), pp. 430, 431.

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APPENDIX A

INSTALLATION & MAINTENANCE

A.1 System Description

The mechanical components of the 50,000g accelerometer calibration system were constructed as described in the main body of this report (see Figure 5 - Assembly of mechanical system, and Figure 16-Miscellaneous parts drawings) with the exception of minor improvements such as bolted clamp segments along the length of the coil's external leads and a ratchet bar that prevents the pendulum from swinging back and possibly damaging the accelerometer or the face of the coil. The total weight of the pendulum assembly turned out to be 43.5 lbs. (19.7 kg), while the test plate with a 25 gram accelerometer weighs .896 lbs. (406 grams), with a mass ratio of 48.5:1.

Electrically, there was a major change made in the switch used for dumping the capacitor's energy into the electromagnetic coil. Rather than use of movable spheres or needles as described in the design section of this report, it was decided to employ an ignitron switching system. Figure A-1 shows the overall wiring diagram including the ignitron and its trigger circuit. Major components are as follows:

(1) Power Supply - Universal Voltronics (Mt. Kisco, N.Y.) Model BAP-10-5.5. This is a 10 kV power supply with a maximum charging current of 5.5 milliamps (approx. 6 minutes to charge the 400 microfarad capacitor to 5 kV). See Appendix C for instruction manual.

(2) Capacitor and Bus Assembly - Maxwell Laboratories, Inc. (San Diego, Calif.) supplied the 400 microfarad, 5 kV, 5 kJ Capacitor No. 33501 and the bus assembly, including the 330 ohm charging resistor and Ignitron Model 95-00865 (similar to GE Model GL7703, 25 kV, 100 kiloamps). See Appendix D for GE's pamphlet on ignitrons.

(3) Coil - The coil was made by Everson Electric Co. (Lehigh Valley, Pa.) essentially as described in Figure 10. As fabricated, the coil contains 16.5 turns. It has been potted in an epoxy cylinder 12.7 cm in diameter and 10.2 cm long, into the back of which are drilled and tapped $\frac{1}{4}$-20 holes. The coil assembly components (epoxy cylinder, mounting plate, and a 2.54 cm plywood spacer) are bolted together by eight $\frac{1}{4}$-20 bolts.

(4) Ignitron Trigger Circuit - Maxwell Laboratories, Inc. supplied the trigger circuit. This circuit is triggered by an ordinary 12V d.c. battery after it has been charged up with 115 V.

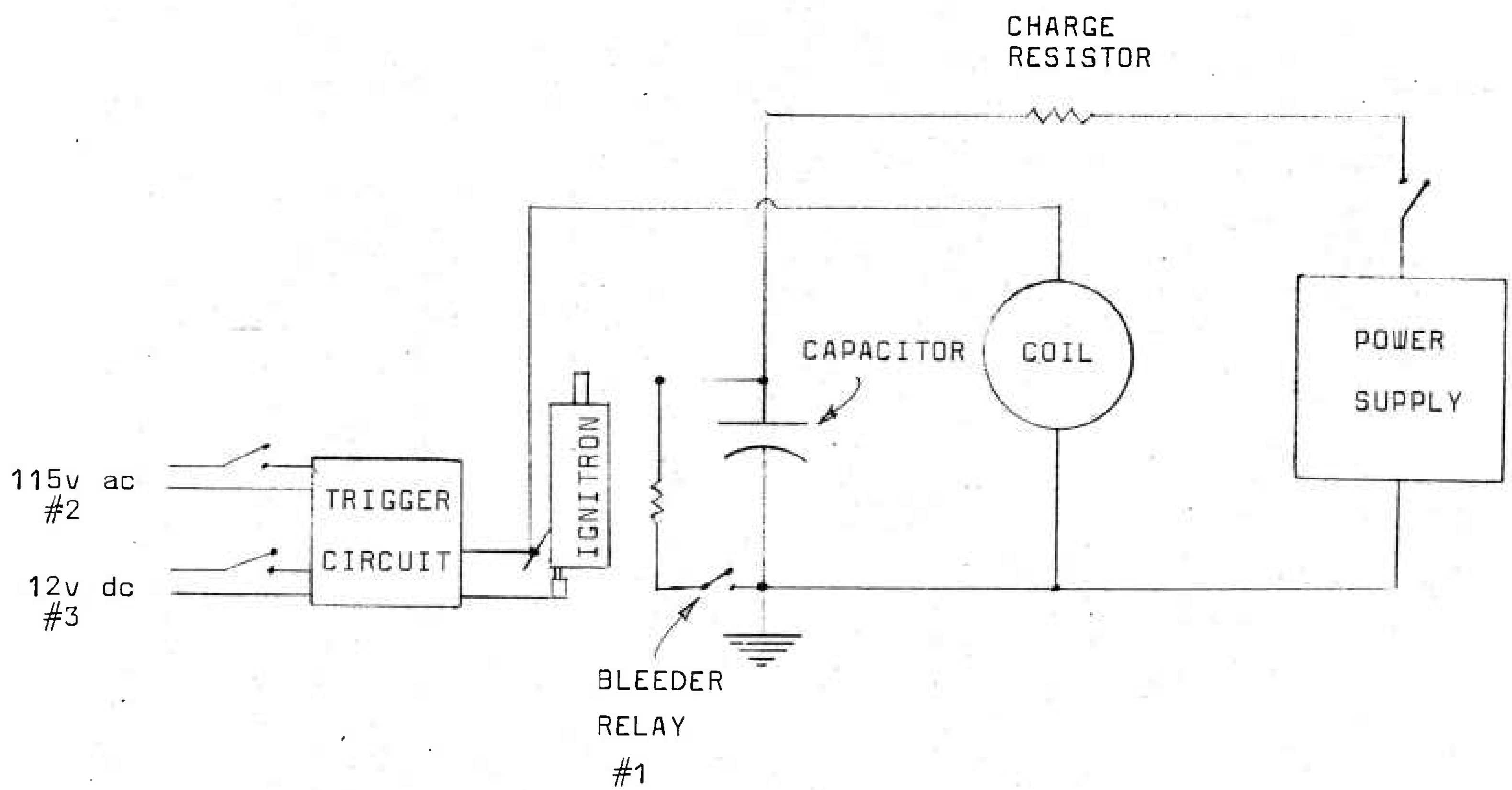


Figure A-1. Overall Wiring Diagram

(5) Capacitor Bleeder Relay - A high voltage relay was procured from Ross Engineering Corp.(Campbell, Calif.) as a major safety feature of the potentially lethal electrical system. When 115 V power is not applied to this relay it shorts the capacitor to ground, thereby bleeding off any residual charge that may remain after a test has been run. It is Model E-12NC, rated at 12 kV. A 5 kohm, 225 W resistor (Ohmite No. 1364) is used to bleed the charge to ground.

The pendulum velocity transducer system described in Chap. 5 of this report was not employed. Because of anticipated difficulties in holding the end of the transducer's probe in contact with the pendulum (which moves vertically as well as horizontally) and expectation that the velocity transducer itself would have to be calibrated, it was decided to use a sliding pencil system to record the pendulum swing on paper. Accordingly, the pendulum has mounted on its rear face two sliding pencil indicators that record the pendulum's maximum swing. Any lateral reactions of the pendulum to impact with the accelerometer plate are recorded as differences between the two pencil traces, which are averaged. The recording paper is mounted on a clipboard tilted about 11° from the horizontal in order to minimize the vertical sliding motions of the pencils. With this arrangement the pencils move less than about .95 cm even though the vertical motion of the pendulum is about 2.54 cm when it swings 15.24 cm horizontally. Measuring the pencil trace to within about .051 cm leads to an error of about 0.3 percent for a 15.2 cm swing of the pendulum.

A.2 Installation

Mechanical installation of the calibration system is a simple matter, since the 25.4 cm steel channel on which the angle iron suspension framework is mounted does not have to be bolted down. The 1.5 m long channel may be located on any reasonably level work bench, table, or desk with access to two 115 V outlets, and access to a secure storage cabinet. The only mechanical requirement is to brace the rear of the coil assembly (see Figure 5) against a nearby wall or floor support (not attached to the channel nor to the table on which the channel rests) in order to prevent excessive flexure of the coil's leads, which could lead to mechanical fatigue.

As a safety measure, it is recommended that all high voltage components are housed in a grounded cabinet that is kept locked and clearly marked with warning signs. In this installation, the coil's leads enter the cabinet through a 7.6 cm diameter hole in its back, since the cabinet is backed against the work table. Another hole (2.54 cm diameter) in the side of the cabinet accepts the low voltage leads from the operator's control box, as follows:

(1) 115 V line to operate the capacitor bleeder relay.

(2) 115 V line to charge the trigger circuit.

(3) Switch line to operate the 12 V trigger.

To house the capacitor, trigger circuit and 12 V battery, the cabinet size must be approximately 1.2 m wide x .46 m deep x .91 m high, or larger.

A.3 Safety Measures

Mechanical safety measures are minimal, since the only potentially dangerous moving part is the accelerometer mount. This plate moves only a short distance (less than 2 cm) at high velocity (of the order of 150 fps or 46 m/sec), but it could be a dangerous missile if it somehow missed or bounced off the pendulum. Accordingly, two safety measures are recommended:

(1) Personnel should not be permitted in the "line of fire" of the coil.

(2) A clear plastic shield, of the order of 1cm or more in thickness, should be located between the operator and the framework during each test.

Careful attention to electrical safety is mandatory, since the high voltages are potentially lethal. The following procedures are recommended to supplement the basic safety afforded by the fail-safe charge bleeder relay:

(1) Warning signs should be displayed prominently to keep unauthorized personnel away from the work area.

(2) The operator control box, calibrator framework and channel, power supply, cabinet and contents must all be grounded.

(3) The cabinet must be locked securely, and warning signs placed on the cabinet to keep unauthorized personnel out.

(4) When the cabinet is opened to perform any work on the electrical components within, it is recommended that the authorized personnel make certain the capacitor is shorted to ground while the work is being performed. Regardless of the apparently proper functioning of the high voltage relay, it is recommended that a shorting connector is attached from the capacitor's anode to ground. A special shorting device should be employed, consisting of two heavy clips with a bleeder resistor in between, mounted so that the operator does not touch any conductors while attaching the clips to anode and ground. The shorting device should be left attached whenever the cabinet is open.

(5) For additional safety (but not to replace the procedure recommended above), the cabinet doors may be designed to automatically short the capacitor to ground whenever they are open.

A.4 Maintenance

There are no routine procedures required for maintenance of the components of the calibration system. All electrical components are rated for thousands of operations before failures are expected. With the exception of the 12 V battery which is easily replaced, it is recommended that the manufacturer of the electrical component in question perform any repairs when necessary.

Replacement of the pendulum suspension wires may be required when mechanical fatigue occurs. The wires employed in this installation are 15 mil steel music wires, 91.4 cm long. They may be purchased at a hobby shop, as well as the balsa rods from which the energy-absorbing balsa cubes are cut.

Note that any adjustments to the bleeder resistor should be made with care. The set screw should be loosened completely before moving the lug, and it should not be over-tightened.

APPENDIX B

OPERATING PROCEDURES

B.1 Test Procedure

The mechanical parameters that enter into the equations for velocity must be measured at the outset of each test series. Pendulum wire length is most accurately measured as slant length L* and then corrected to vertical hanging length L through use of Figure B-1. Also included in the figure is the correction to convert pencil mark length X* along the sloping clipboard surface to horizontal swing X. If the clipboard is used with angle θ different from the 11° slope:

$$X = X^* \cos\theta \qquad \text{(B-1)}$$

Masses that enter into the momentum-exchange equation must also be checked at the beginning of a test involving a different accelerometer. Any changes made to the original masses of the pendulum (43.5 lbs. or 19.7 kg) and test plate (.896 lbs. or 406 g when it holds a 25 gram accelerometer) should be recorded and the accelerometer weighed. For the most accurate weight, the cable connector plus about 2 mm of the flexible lead should be added to the mass of the accelerometer itself. Any difference between this total mass and the nominal 25 grams can be corrected with the use of the "Correction for Mass" curve on Figure B-2. Figure B-2 contains curves for accelerometer velocity vs. pendulum swing X, with corrections for pendulum wire length and mass.

After measuring the accelerometer's mass and mounting it on the test plate, the balsa blocks are taped on the impact face of the pendulum. Then the coil/plate/pendulum system should be aligned by means of the wire adjusters. After alignment, the test plate must be resting against the face of the coil (any gap would reduce the force delivered to the plate) and there must be some small gap (of the order of 5 mm) between the opposite face of the test plate and the balsa blocks (to prevent balsa block deceleration resistance while the test plate is being accelerated).

When accelerometer mounting and system alignment is completed, the sliding pencil indicators are adjusted to be sure they make satisfactory contact with the recording paper throughout the anticipated pendulum swing. The ratchet bar is placed in its functioning position and the pendulum is allowed to come to rest. At the time when no further disturbances to the pendulum will be introduced, the recording paper is slid gently some small distance normal to the swing direction so that the zero positions of the pencils are

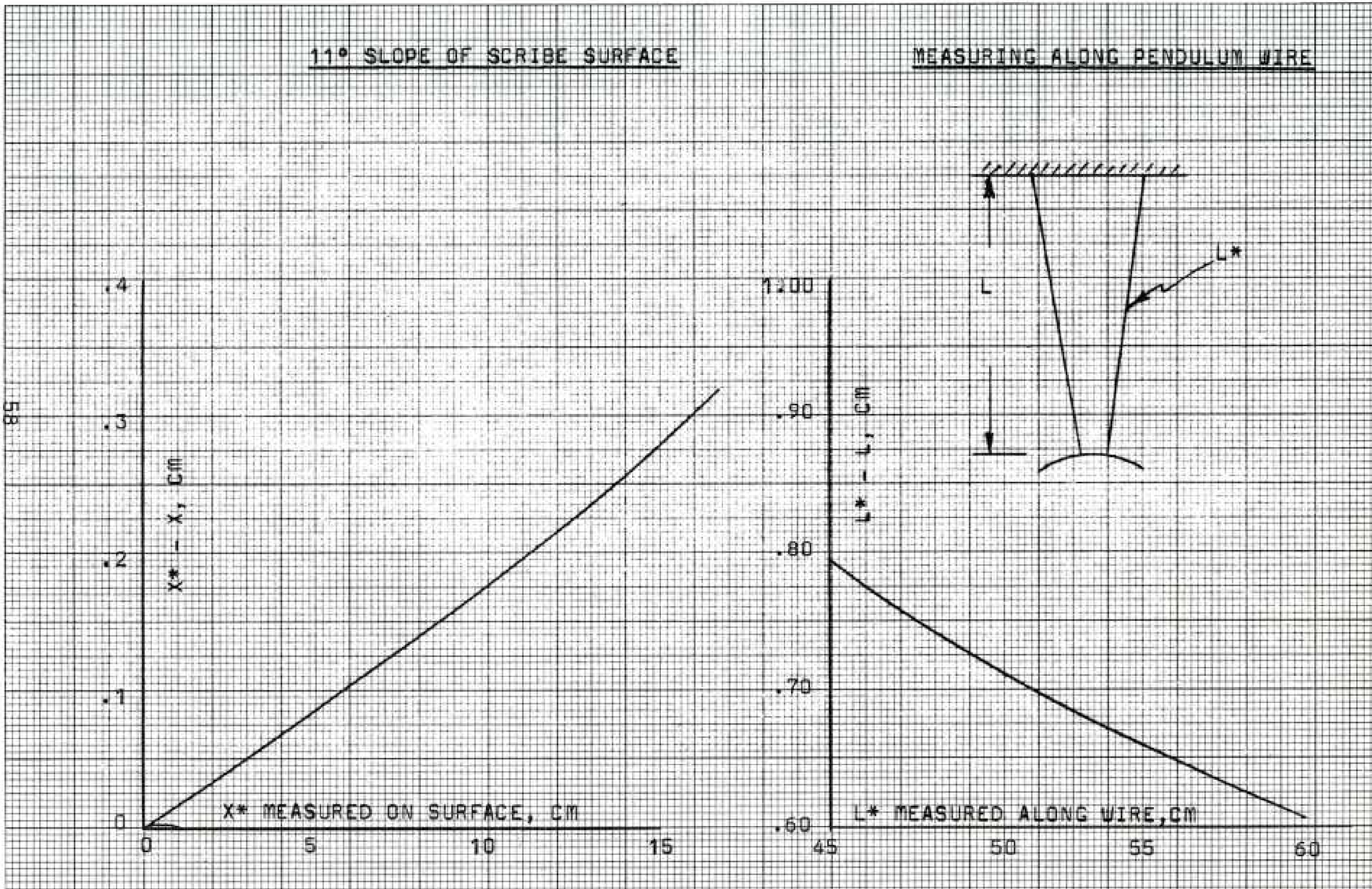


Figure 8-1. Corrections in Measuring X and L

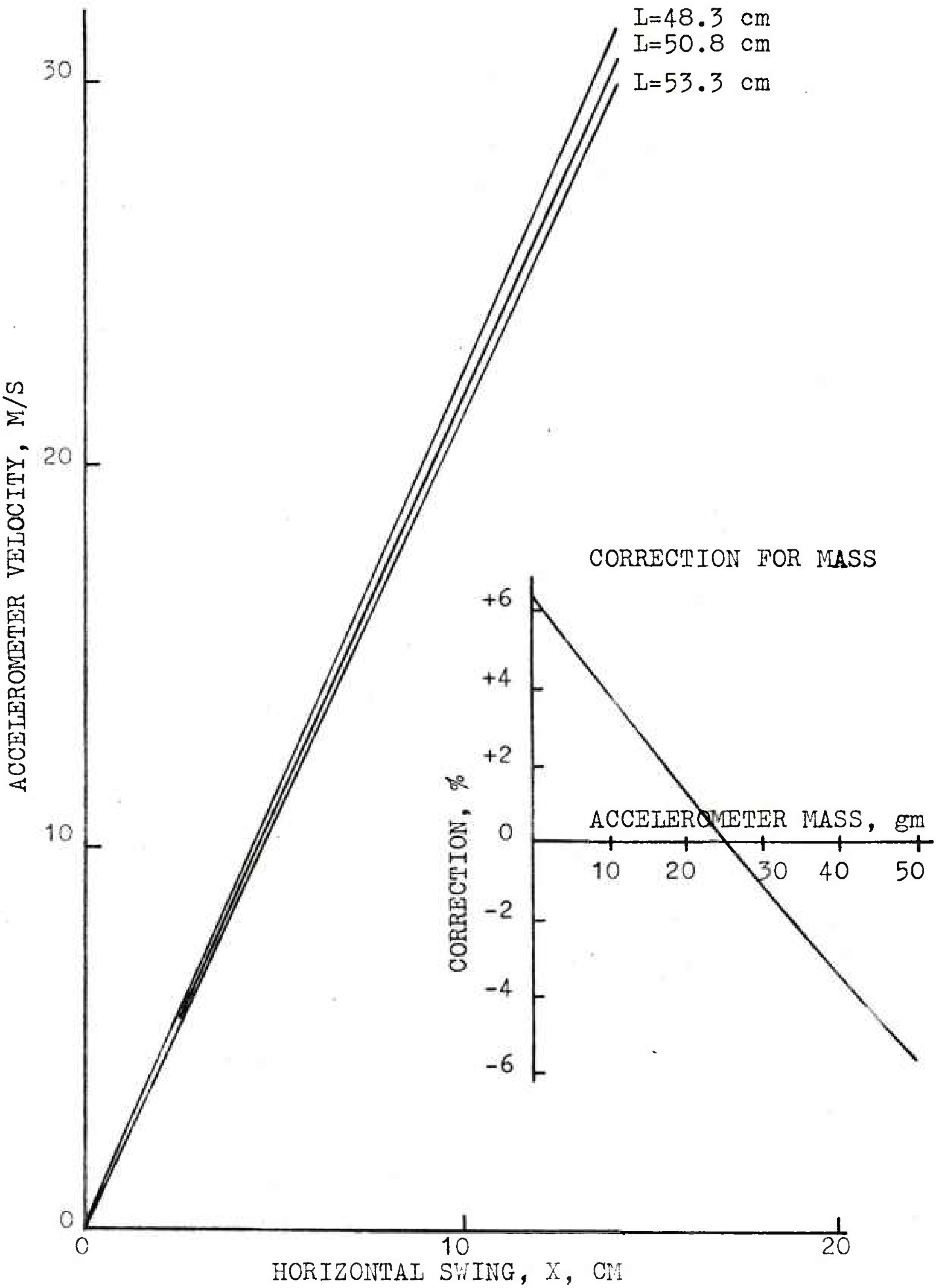


Figure B-2. Accelerometer Velocity vs. Pendulum Swing marked clearly. The mechanical system is now ready to be activated by the electrical system in the following firing sequence (as marked clearly on the operator control box):

(1) 115 V is supplied to the high voltage relay by switching #1 to the "on" position. This causes the relay to open (no longer shorting the capacitor to ground) in order for the capacitor charging process to begin.

(2) With the voltage control knob set at zero, the power supply switch is turned on. The High-Voltage-On button is pressed and the red indicator light shows that charging may proceed.

(3) Switch #2 is turned on, thus charging up the trigger circuit.

(4) The power supply voltage control knob is turned <u>very slowly</u> to charge the capacitor. If the knob position is advanced at any time more than about 400 volts above the reading of the capacitor voltage gage it may cause the overload switch to function (white indicator light). In this case the control knob should be backed down to a position below the gage reading, the overload reset button pushed, the high-voltage-on button pushed, and the charging process continued. Charging is a slow process, requiring about 5 minutes to reach 3 kV.

(5) When the capacitor voltage has been increased to the desired level, the power supply is turned off.

(6) A final check on all instrumentation should be made before firing.

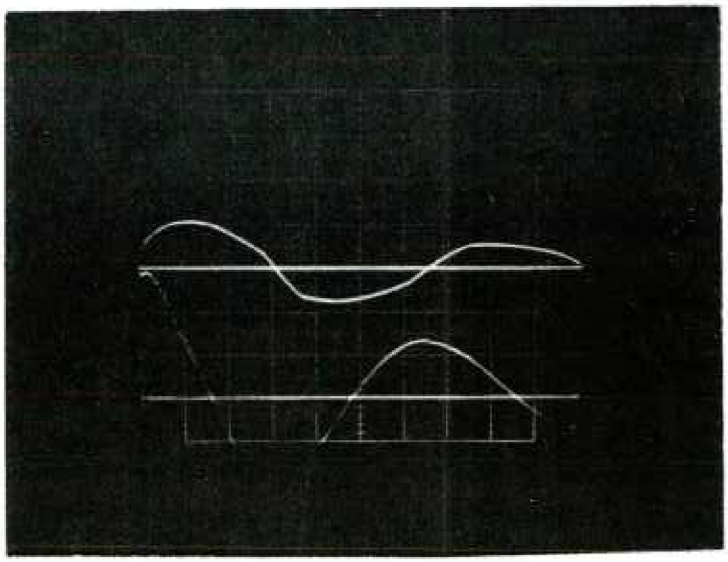
(7) #3 switch applies 12 V to the trigger circuit in the "on" position, thus firing the system.

(8) All switches on the operator control box are turned off. This insures that any residual charge on the capacitor is bled to ground.

(9) The pendulum may be released from the ratchet after the swing recording paper is removed.

B.2 <u>System Performance</u>

Electrical performance of the coil circuit has been determined by measuring voltage and current through the coil. Figure B-3 shows the voltage (lower trace) starting at time zero at 3 kV, dropping to zero in about 80 microseconds, then



SWEEP: 50 microsec./div.

CURRENT: 10 kA/div.

VOLTAGE: 1 kV/div.

Figure B-3. Coil Current and Voltage When Capacitor at 3 kV going to a negative peak of about 2 kV, then positive to a peak of about 1.3 kV, and so on in a damped oscillation with a period of about 350 microseconds. The upper trace on Figure B-3 shows a peak current of 10 kiloamps and about 150 microseconds duration of the first positive pulse. Since Eq.(5) indicates that field strength B is proportional to current and Eq.(6) indicates that magnetic pressure P is proportional to B^2, the pressure and force and acceleration are theoretically proportional to current squared. However, since the test plate is moving away from the coil, one can expect diminishing effects of the current oscillations after the first positive pulse.

Figure B-4 shows the accelerations experienced by an accelerometer mounted on the test plate. The lower record shows a high initial acceleration pulse with about a 150 microsecond positive duration (note that the accelerometer's oscillations with a 15 microsecond period are superimposed on the input accelerations), which corresponds to the current's initial positive duration. Subsequent responses of the accelerometer are reduced-amplitude versions of the current's damped oscillations; however, they appear as damped acceleration oscillations with a period of about 90-100 microseconds. The upper record on Figure B-4 shows the deceleration pulse that occurs when the test plate crushes the balsa blocks. The key performance feature illustrated by Figure B-4 is the first positive pulse duration of 150 microseconds. According to Eq.(1) the accelerometer's natural period should be 50 microseconds or less (natural frequency 20 kHz or greater) for good calibrations with this calibration system.

Figure B-5 presents some results of velocity calibrations using pencil swing indicator data. Test plate velocity may be estimated by the following empirical fit to the curve in Figure B-5:

$$V = 3.11(kV)^{2.29}, \text{ m/s} \qquad \text{(B-2)}$$

Note that the exponent is not far from the theoretical value of 2.00.

If the first positive acceleration pulse with 150 microseconds duration and half-sine form factor of .636 were the only contributor to producing V of Eq.(B-2), the accelerations delivered by the system would be V/.636(.000150)(32.2) as follows:

$$g_1 = 3{,}320(kV)^{2.29}, \text{ g units} \qquad \text{(B-3)}$$

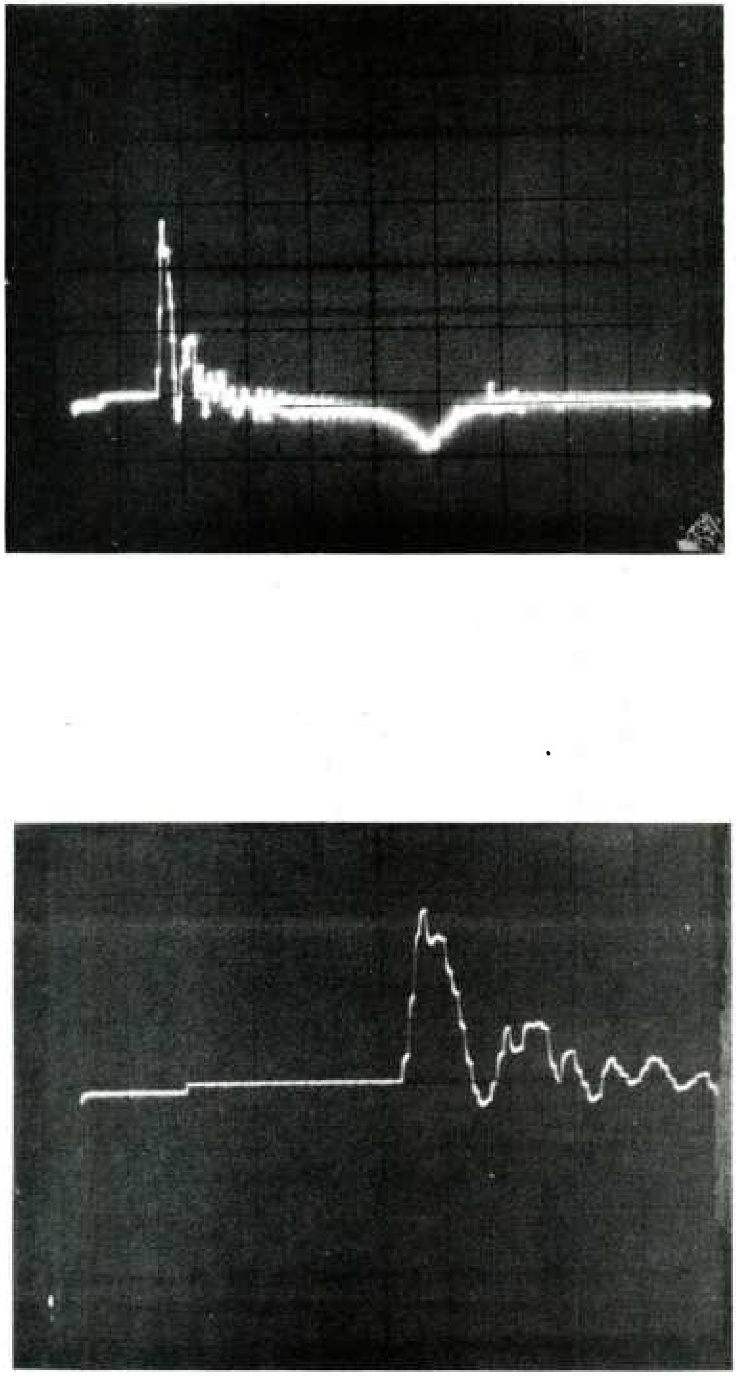


Figure B-4 Response of Accelerometer With 15 microsecond Natural Period.

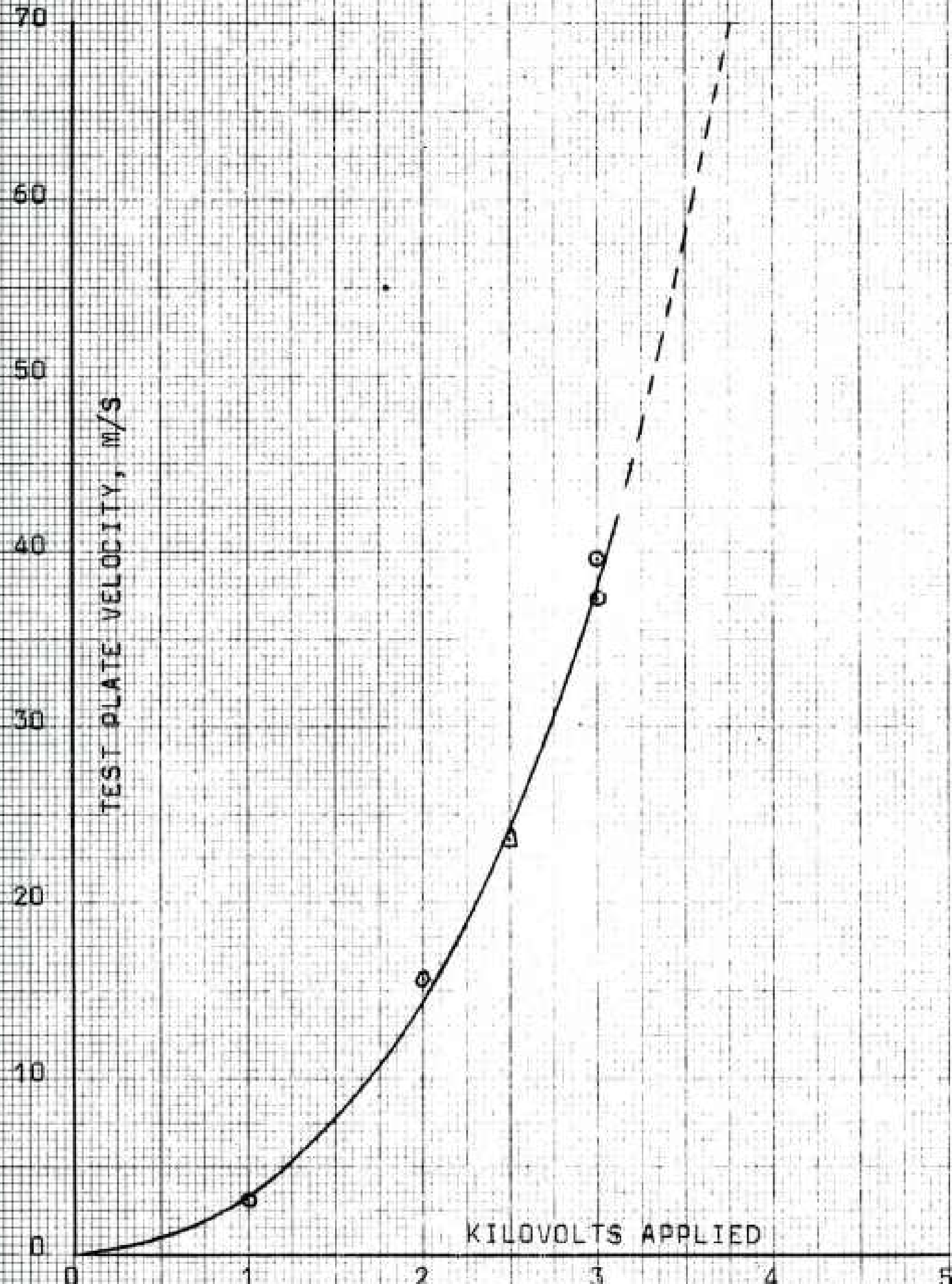


Figure B-5. Velocity of the Test Plate

Analysis of the acceleration history of Figure B-4 including the accelerations after the first positive pulse, however, shows that the first peak was only .75 times the value given in Eq. (B-3). If this ratio is found to hold at all acceleration levels:

$$g_1 = 2{,}490(kV)^{2.29}, \text{ g units} \qquad (B-4)$$

Table B-1 presents peak acceleration values according to Eq.(B-4).

Table B-1. Peak G According to Eq. (B-4)

kV	1	2	3	4	5
g_1, g units	2,490	12,200	30,800	59,600	99,300

Another noteworthy feature of Figure B-4 is that the test plate's oscillations, estimated to be at 20-30 k Hz, do not appear to have been excited to any great extent. It is likely, therefore, that the thickness and mass of the test plate may be reduced somewhat without introducing objectionable oscillations, thus increasing the g_1 output capability of the calibrations system at all voltages.

B.3 Calibration of Accelerometers

At such time that the user of this high-g calibration system has calibrated certain accelerometers and found them worthy to serve as reliable "standard" accelerometers, it will be a very easy matter to employ this system. The test accelerometer and the "standard" may be mounted side-by-side on the test plate and their outputs compared, without the necessity of using the pendulum for measuring velocity. Until the user has found such a "standard" accelerometer, however, the following method of calibration will be necessary.

Two measurements are basic to this method of calibration, the velocity change experienced by the accelerometer and the voltage vs. time output of the accelerometer while it is being brought up to this velocity. Velocity $\dot{X}$ is calculated from the maximum swing of the pendulum by means of Eqs. (13) and (14) or Figure B-2, or by independent measurements of pendulum or test plate velocity. If the accelerometer's outputs are expressed in terms of millivolts per g:

$$\dot{X} = \int \ddot{X} dt = \frac{g}{mV} \int (mV) dt$$

$$\frac{mV}{g} = \frac{\int (mV) dt}{\dot{X}} \tag{B-5}$$

The quantity $\int (mV) dt$ is calculated as the area under the millivolts vs. time output of the accelerometer. Some oscilloscopes can provide this calculation directly, while others provide digital data that can be integrated by computer. In any case, it is important to continue the integration past the first positive pulse to account for the velocity that may be contributed by the subsequent oscillations (see the difference between Eqs. (B-3) and (B-4) for example).

Note that the accelerometer's mV/g constant determined by Eq.(B-5)is an average value for the range of accelerations experienced in the particular test. If the accelerometer is non-linear, a second test at a higher or lower peak acceleration will yield a different mV/g "constant". Accordingly, it is recommended that tests are run at several levels leading up to the accelerometer's rated limit as a means of determining its linearity.

APPENDIX C

POWER SUPPLY

HIGH VOLTAGE POWER SUPPLY INSTRUCTION MANUAL

MODEL NUMBER BAP-10-5.5

SERIAL NUMBER ______________

high voltage leadership

UNIVERSAL VOLTRONICS CORPORATION
27 Radio Circle Drive, Mount Kisco, N.Y., 10549
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UNIVERSAL
VOLTRONICS CORPORATION
27 Radio Circle Drive, Mt. Kisco, N.Y. 10549
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TWX # 710-571-2142

OPERATING INSTRUCTIONS FOR PORTABLE HIGH VOLTAGE DC POWER SUPPLIES - BAP SERIES

Table of Contents:

UNIVERSAL
VOLTRONICS CORPORATION
27 Radio Circle Drive, Mt. Kisco, N.Y. 10549

TWX # 710-571-2142

WARRANTY AND SERVICE POLICY

1.0 Introduction:

Universal Voltronics Corp. has developed and installed a considerable number of high voltage power supplies and control equipments. In order to achieve optimum performance and maintain good customer relationships, UVC maintains a full-time field service organization giving both national and international coverage to take care of cases of pre-turn-on meetings, initial turn-on, as well as repair problems.

All UVC power supplies are completely factory-tested and warranteed per the attached document. It is to be recognized that unusual operating conditions arise in the field which are of such a nature as to make it impossible for a manufacturer of electrical equipment to simulate in factory tests. The final test is operation with the customer load and ambient conditions.

With this as background, UVC reviewed the various problems and offers the following program to assist its customers in getting prompt turn-on, reliable operation and rapid field service.

2.0 Initial Turn-On:

UVC makes available qualified engineering personnel to be present at the site to assist the customer before and during the initial turn-on to verify proper electrical performance. This includes wiring checkout between input mains and the high voltage output terminal. A complete electrical check is made to verify that the equipment has been installed and set up properly. (See cost schedule below, #5.0.)

3.0 Field Repair and Service Responsibility:

(Repair, Application Analysis, Circuit Improvement, etc.)

Based on our experience, we find that there are three main areas of definition as regards field service problems, as follows:

3.1 Full UVC Responsibility:

This covers the case (within the warranty period) where the equipment furnished by Universal Voltronics Corp. does not operate properly due to manufacturing or design defects. This would include such things as voltage control not functioning properly, transformer-rectifier failure, metering errors, etc. These are clearly UVC's responsibility, would be considered in-warranty repairs, and all repair costs would be absorbed by UVC.

3.2 Customer Full Responsibility:

This covers the case (whether it be in or out of warranty) in which the customer has mis-applied or misused the equipment. Examples of this would be undersized or oversized equipment. This could happen when the customer has not had the opportunity to fully test his system and hence finds that the device furnished by UVC does not match the characteristics of his load. Another example is equipment damage resulting from electrical mis-wiring in the field, causing damage to the electrical parts. These are cases where all costs are paid by the UVC customer.

3.3 Joint Responsibility:

This covers the case where UVC and the customer have worked jointly on a project where all the parameters were not fully established during the design and conception stages. In this particular case, UVC will make available competent personnel to assist in the engineering to adapt to the particular site requirements. In the case of joint responsibility, the rates are to be negotiated between UVC Service Department and the customer. The final costs depend on the specific situation and should be agreed upon during the pre-contract period.

4.0 Shipping Damage:

We have found that on occasion, equipment arrives at the site damaged due to rough handling in shipment and installation at site. The difficulty is that the processing of a claim for shipping damage is generally beyond the control of UVC.

We assume that once the equipment arrives at the site, it is inspected by the customer's personnel and a claim processed in the event of shipping damage. We would, of course, repair and rework the equipment, either at the site or at the factory, depending on the extent of the damage. It is to be recognized that these repair costs will not be absorbed by UVC.

5.0 Rates:
The following rates apply to all of the cases cited:

5.1 Engineering Personnel: $350 per day.

5.2 Technician: $250 per day.

5.3 Travel Expense: Direct transportation costs for air, car, etc.

5.4 Hotel and Meal Costs:

5.5 Local personnel, fork lifts, hoists, cranes, etc.: Costs per local rates - to be paid by customer.

6.0 Spare Parts:
UVC maintains spare parts on most of the control circuits as well as the high voltage assemblies. It does, in some cases, stock transformers. Our customers should check with our Service Department for recommended spares and these should be maintained in the field in order to have continuity of operation.

7.0 Service and Warranty:

7.1 Shipping Damage:
The power supply should be inspected and tested immediately upon arrival. In the event the unit fails to operate properly or is damaged in any way, the carrier should be notified at once. When the claims agent has inspected the shipment and prepared a report of damage, a copy of this report should be sent to us. At that time, we will advise you concerning the repair or replacement of the power supply.

7.2 Service and Information:
All questions concerning the operation or malfunctioning of this instrument should be directed to our representative in your immediate area. If there is no representation in your area, then contact the factory directly. NOTE: Include model and serial number in all correspondence concerning this power supply. Without this information, we will not be able to give you prompt service. If the shipment should be returned to the factory, we will send you a Shipping Release and a tag which should be filled out and affixed to the unit. Do not ship a unit to the factory without this tag, unless specific authorization has been received to do so.

7.3 Shipments:
All shipments to UVC must be prepaid unless we authorize to the contrary. The power supply should be wrapped in heavy paper and packed in the original container or a wooden box with shock-absorbent material on all sides. DO NOT SHIP THE UNIT WITH OIL. Make certain that all tubes (if any) are removed and shipped separately. All movable objects such as the tube plate caps, solenoids, etc. should be fastened securely. Please return instruction manual with unit to be repaired.

7.4 Warranty:
This high voltage power supply is warranteed by Universal Voltronics Corp. to be free from de-
:s in material and workmanship. Our obligation to the original purchaser under the warranty is limited
servicing the instrument and replacing defective parts when the equipment is returned prepaid to the
ctory, with the exception of tubes, on which there is only the manufacturer's guarantee. This guarantee
s valid only if the instrument has not been abused mechanically and the operational limits prescribed in
.ne instruction manual have been adhered to.

The period of warranty is one year after date of shipment* to the original purchaser. Removal of
erial plate or defects caused by improper operating conditions, accidents, misuse or negligence will
oid the warranty.

* ..te of shipment is that evidenced by the Bill of Lading.

III. OPERATING INSTRUCTIONS

A) PRELIMINARY SETUP:

The power supply is portable and hence final operating location and mounting is not critical. It can operate in any position. The equipment has been provided with a 3-wire input plug with the third wire being ground. It is mandatory that the power supply be operated with a ground connection. If a 3-wire outlet is not available in the laboratory or test area, then run a ground jumper to the stud on the chassis rear.

B) POLARITY SETTING:

These adjustments should be made with the line cord disconnected from the mains. There are two adjustments that are required in order to set for the desired output polarity. The first adjustment is the setting of the power pack chassis. Lay the cabinet on its side and remove the screws that hold the chassis bottom cover plate. There is a permanent connection of the output cable to the center terminal which is the junction of the resistor and a high voltage termination. The two leads from the power supply are respectively labelled positive and negative. In order to operate with positive output, connect the positive lead to the high voltage terminal and the negative lead to ground. In order to operate in the opposite polarity, proceed in the opposite fashion. The terminations are of a rapid disconnect type.

Replace the bottom cover plate.

The next step is to set the meter polarity selector switch located on the front panel between the two meters to correspond to the polarity set in the high voltage compartment. This front panel switch only sets the polarity of the meters. It has been located on the front panel as an added convenience to the operator as it indicates the polarity under which the equipment is operating. If a mistake is made in either the high voltage compartment or on the front panel, the meters will read down scale. There is no danger of damage as the meters are protected.

CAUTION: DO NOT OPERATE WITH BOTTOM COVER PLATE IN PLACE.

C) TURN-ON:

The operation of the equipment is straightforward. Throw "Main" toggle switch to the On position. Swt "Voltage Control" T-1 to zero. This control is interlocked so that no high voltage can be turned on with the control off zero. The operator should be alert that zero start is required.

Depress the "High Voltage On" pushbutton. The red "High Voltage On" light should be illuminated. If it is not, then the voltage control is not at zero.

To turn the equipment off, the operator should depress the "High Voltage Off" pushbutton. Throwing the "Main" toggle switch to the Off position will also turn high voltage off.

D) OVERLOAD - RESET:

An overload relay K-1 has been included to protect the load and the power supply against severe short circuits. This relay is in series with the low end lead in the high voltage circuit. In effect, this relay senses true output current. In case of an overload due to a short circuit, the current flowing through the relay coil (K-1) will activate relay K-2 which, in turn, will disable primary power. The pilot light "Overload" will shine.

In order to reset, the operator must depress the "High Voltage Off-Reset" pushbutton. This will release the locking relay K-2. The next step is to set the output voltage control to zero and depress the "High Voltage On" pushbutton. The operation will be per the Turn-On steps above. If, for any reason, the output fault has not been cleared, then the overload will continue to trip out.

E) FUSES:

A fuse has been included in series with the "Main" line (labelled "Main") and is located on the front panel. Also included is a fuse in series with the Primary of the High Voltage transformer, also front panel mounted (labelled "Primary"). These fuses act as backup protection for the overload relay in case of failure. The overload relay is the major protective device with fuses being used for added reliability. Fuse values are given on the wiring diagram.

IV. THEORY OF OPERATION (See schematic in rear)

This is the straightforward, well-known locking circuit. Power appears at switch S-2 (High Voltage On) after the main toggle switch is thrown. Depressing this "High Voltage On" switch allows power to flow through the interlock switch S-4 (assumed to be closed) and energizing relay K-3 through wire #20. K-3 pulls in and locks in across the line by means of its own contacts 3A. This, therefore, requires that S-2 only be of the momentary push-button type. After the relay pulls in, power is available at the "Voltage Control" T-1 and the pilot light I-2, "High Voltage On", is illuminated. By depressing the "High Voltage Off" pushbutton S-1, the operator momentarily interrupts power to relay K-3 which then drops out. It releases its contacts 3A so that when S-1, the "High Voltage Off" pushbutton is released, K-3 is dropped out and stays dropped out.

B) OVERLOAD-RESET CIRCUIT:

The action of the overload circuit is also straightforward. In the event of an overload, relay K-1 pulls in momentarily closing its contacts 1A. These contacts are in parallel with contacts 2A of relay K-2. This overload therefore actuates and locks in K-2 through its contacts 2A, while simultaneously opening up contacts 2B. Contacts 2B opening will instantaneously disable primary power. Note that simultaneously, the "Overload" light I-1 is illuminated as it is in parallel with the holding relay coil K-2. This circuit stays locked until such time as the "High Voltage Off-Reset" pushbutton is depressed. This then disables the relay K-2 and allows the operation to proceed per previous discussions.

It is important to note that the overload relay K-2 pull-in is a momentary one to initiate the locking action. The instant that primary power is disabled, the output current should be zero (decaying to zero) so that relay K-1 drops out. However, K-2 has picked up, locking out, and is independent of K-1 thereafter.

C) KILOVOLTMETER AND MILLIAMMETER CIRCUIT:

The operation of these circuits is almost identical. The kilovoltmeter M-1 has in series with it a resistor R-3 which is used to fire the neon lamp I-4 in case of transient surges. Capacitor C-2 is utilized to bypass transients which take place more rapidly than the ionization time of the neon I-4.

C) KILOVOLTMETER AND MILLIAMMETER CIRCUIT: (Con't)

Multiplier resistor R-5 is designed to provide a feedback current proportional to output voltage. The kilovoltmeter dial has been calibrated in terms of output voltage, hence true output voltage is read in this fashion.

The milliammeter circuit operates in an analogous fashion, where R-4, C-1 and I-3 perform essentially the same functions as R-3, C-2 and I-4, described above. The neon fires in the event of an overload and bypasses the majority of the overload current and protects the meter M-2.

D) HIGH VOLTAGE POWER PACK:

The high voltage power pack employs solid state rectifiers connected either in a full-wave bridge or in a full-wave voltage doubling circuit (see wiring diagram). There is included inside the pack series resistors to limit discharge currents in the event of short circuit.

V. SERVICE ACCESS

A) TOP COVER HOOD:

Remove the screws on the sides of the cover. Removing this cover hood gives access to controls and the power pack. If it is desired to drop the front panel, then the screws on the bottom of the front panel should be removed.

B) CHASSIS BOTTOM COVER PLATE:

The reversing assemlby as well as the multiplier resistor R-5 is located inside the bottom of the chassis. Removing the four corner screws is a simple matter and allows rapid access.

VI. DRAWINGS AND REPLACEMENT BILL OF MATERIAL

Included in this section are the following:

A) Wiring Diagram

B) Replacement Bill of Material

UNIVERSAL VOLTRONICS CORPORATION
27 Radio Circle Drive, Mount Kisco, N.Y., 10549
(914) 241-1300

February 1976
Replacement Bill of Material
BAP(Original 1 case)

Wiring Diagram
Dwg. No. C-6-1-20
Page 1.

Schem. No.	Description			Qty.
C-1, 2	Capacitor, 0.25 mfd @200 volts			2
C-3	Capacitor(OI Bypass), .1 mfd @600V centralab DF 104			1
C-4, 5	Capacitor(Surge bypass),.01 mfd @1KV centralab "Gapcap" Z5U			2
F-1, 2	Fuse, BAP-10-1.5 type 3AG 1 amp			1
	BAP-10-5.5 type 3AG lamp			1
	BAP-16-1.5 type 3 AG 1 amp			1
	BAP-16-5.5 type 3 AG 2 amp			1
	BAP-22-1.5 type 3 AG 1 amp			1
	BAP-22-5.5 type 3 AG 2 amp			1
	BAP-32-1.5 type 3 AG 1 amp			1
I-1, 2	Lamp, Sylvania 120MB (120V-3W, bayonette)			2
I-3, 4	Lamp, NE-2AS			2
I-5	Lamp, NE 2AS 3 in series			3
K-1	Relay(Overload), Kurman #51CA40D			1
K-2, 3	Relay, P&B #KA5AY-115V coil			2
M-1	Meter(KV), Modutec T2S-DUA-100-NL-U DCFSS cal for alum panel.			
	BAP-10-1.5	0-12KV dial	10KV red line	1
	BAP-10-5.5	0-12KV	10KV	1
	BAP-16-1.5	0-18KV	16KV	1
	BAP-16-5.5	0-18KV	16KV	1
	BAP-22-1.5	0-25KV	22KV	1
	BAP-22-5.5	0-25KV	22KV	1
	BAP-32-1.5	0-35KV	32KV	1
M-2	Meter(MA), Modutec T2S, BMA-0015-NL-U DCFSS cal for alum panel			
	BAP-10-1.5	0-1.5MA dial	1.5MA	1
	BAP-10-5.5	0-6MA	5.5MA	1
	BAP-16-1.5	0-1.5MA	1.5MA	1
	BAP-16-5.5	0-6MA	5.5MA	1
	BAP-22-1.5	0-1.5MA	1.5MA	1
	BAP-22-5.5	0-6MA	5.5MA	1
	BAP-32-1.5	0-1.5MA	1.5MA	1

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(914) 241-1300

February 1976
Replacement Bill of Material
BAP(Original 1 case)

Schem. No.	Description			Qty.
R-1, 2	Resistor, Not Used			-
R-3	Resistor, Carbon, 390K, 1W, 10%			1
R-4	Resistor, Dep carbon, 18K, 1/2W, 1%			1
R-5	Resistor(KV Multiplier)			
	BAP-10-1.5	2%RPC matched pair, BP6	BBR115M	1
	BAP-10-5.5	2%, RPC	BBR115M	1
	BAP-16-1.5	2%RPC	BBR170M	1
	BAP-16-5.5	2%RPC	BBR170M	1
	BAP-22-1.5	2%RPC	BBR 240M	1
	BAP-22-5.5	2%RPC	BBR240M	1
	BAP-32-1.5	2%RPC	BFQ-BFT 330M	1
R-6	Resistor, Pot CTSX201R103B or U-39-10KΩ(not used IN 1.5MA)			1
R-7	Resistor, Pot CTSX201R252B or U-39-2KΩ(2.5KΩ)(not used in 1.5MA units)			1
R-8	Resistor, (KV cal), Pot CTSX201R252B or U-39-25KΩ			1
S-1	Switch(Pushbutton), Smith #926			1
S-2	Switch(Pushbutton), Smith #926			1
S-3	Switch(Polarity), Entralab #PA1012			1
S-4	Switch, Micro switch 3111SM1-T			1
S-5	Switch(On-Off), Smith 500			1
T-1	Auto Transformer, All units except BAP-22-5.5 Staco 171 BAP-22-5.5 Staco 251			1
W-1	Line cord, 3 cond#18 w/integral plug 1-347 Birnbach or equal			1
W-2	Output cable, RG 8/U			3ft.
PS-1	Power Pack			
	BAP-10-1.5	BPE-10-1.5		1
	BAP-10-5.5	BPE-10-5.5		1
	BAP-16-1.5	BPE-16-1.5		1
	BAP-16-5.5	BPE-16-5.5		1
	BAP-22-1.5	BPE-22-1.5		1
	BAP-22-5.5	BPE-22-5.5		1
	BAP-32-1.5	BPE-32-1.5		1

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TWX # 710-571-2142

FORM 116

REQUEST FOR SPARE PARTS

Model Number ______________________________

Serial Number ______________________________

Date ____________________

Requested by ______________________________

Position ______________________________

Company ______________________________

Address ____

City ________________________ State ____________________ Zip ______________

Please give following information on use of equipment.

A. Primary use of equipment

B. Duty Cycle per Day ____________ Week ____________ Year ______________

C. Expected overloads or short circuits during normal operation ____________

D. Comments

Send completed form to:
Universal Voltronics Corporation
Service Department
27 Radio Circle Drive
Mt. Kisco, New York 10549

A-2-890-40

UNIVERSAL VOLTRONICS CORPORATION
27 Radio Circle Drive, Mt. Kisco, N.Y. 10549
(914) 241-1300

Date: November 21, 1980

INSTRUCTION MANUAL DELAY REPORT

Customer: 3 C Systems

Address: 620 Argyle Road

Wynnewood, PA Zip: 19096

Attention: Mr. M. Kornhauser

Building or Mail Stop: ______

UVC Model # BAP-10-5.5

UVC Serial # 80-9-5748

Customer P.O. # C-C006-3

Gentlemen:

Please excuse the delay on delivery of the enclosed instruction manuals (1 copies). If you have any questions or problems concerning this item please do not hesitate to contact our sales department. Thank you.

Signed Michele Munnelly

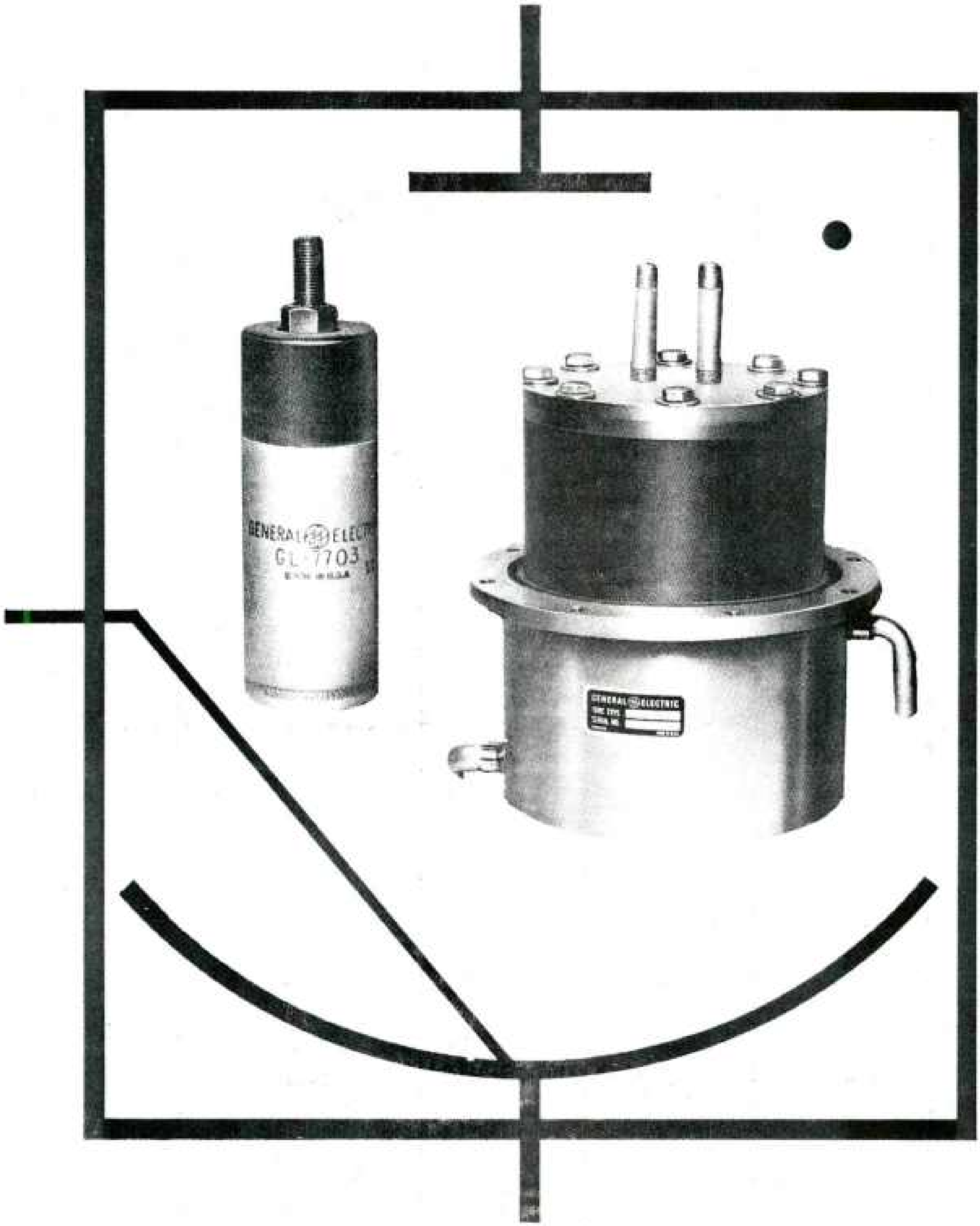
Dept. Sales

APPENDIX D

IGNITRONS

g[illegible]s

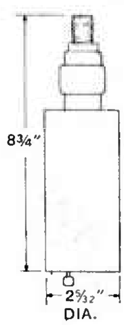
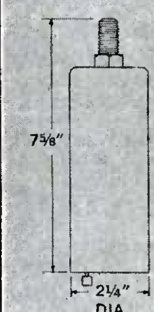
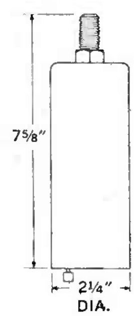
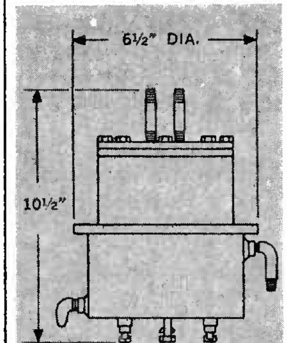
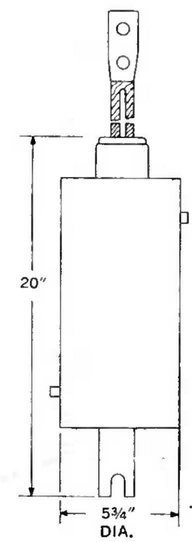
CAPACITOR DISCHARGE AND CROWBAR SERVICE



TUBE PRODUCTS DEPARTMENT

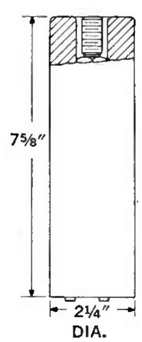
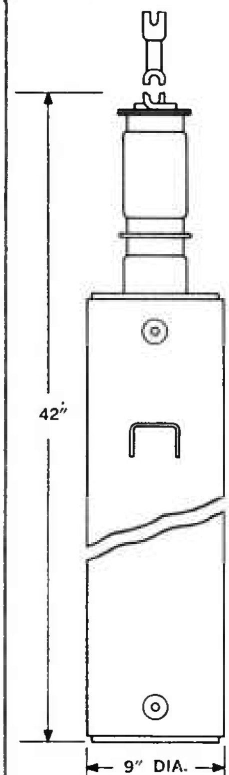
GENERAL ELECTRIC

TABLE I — SUMMARY OF IGNITRON CHARACTERISTICS

Tube Type	GL-7171	~~GL-37228~~	GL-7703	~~GL-37267A~~	GL-37207
Dimensions		(Use GL-7703) 		(No longer available; other types more suitable.) 	(The ignitrons in this table are capable of higher rates but not necessarily at simultaneous maximum ratings.) 
Anode Voltage (kilovolts)	10	20	25 20	25	25
Peak Current (kiloamperes)	35	100	100	300	300
Total Charge (coulombs)	30	30	30		200
Ionization Time (microseconds)	0.5	0.5	0.5	0.5	0.5
Discharge Rate (pulses/minute) typical	2	2	2	100	4 50
Anode Material	Graphite	Stainless Steel	Molybdenum	Molybdenum	Graphite
Cooling	clamp	clamp	clamp	water anode—cath.	water jacket
Rigid length (Inches)	8-3/4	7-5/8	7-5/8	10-1/4	20
Diameter (Inches)	2-5/32	2-1/4	2-1/4	6-1/2	5-3/4

Many of the ratings listed do not represent ultimate tube capabilities. As new tests and field experience establish higher parameters, revisions to published data will be made.

NOTE: Changes in red ink were made in October, 1974.

	GL-5630	GL-37248	GL-6228
	The GL-5630 and GL-6228 are gridded tubes, therefore less suitable than the other types for typical capacitor discharge or crowbar applications. Their particular advantage is for very high repetition rates.		
		(This type will conduct higher peak currents but with greatly reduced life.) 	
	35	50	50
	20	15 25	30
		15	
	0.8	0.5	0.8
		2	
	Graphite	Molybdenum	Graphite
	water jacket	clamp	water jacket
	22-3/16	7-5/8	42
	5-3/4	2-1/4	9

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SCOPE

The ignitron was developed during the 1930's when requirements of power rectification began to extend beyond the capabilities of existing devices. In earliest applications, the ignitron's tremendous switching capability and extreme reliability were utilized primarily in fixed and mobile power rectification applications.

In recent years, new needs in basic research, communications and industrial fields have been met by adaptations of the ignitron to capacitor-discharge switching and short-circuiting of power supplies. Research laboratories of the Atomic Energy Commission apply ignitrons as control switches for megajoule capacitor banks whose discharge is utilized in plasma and controlled fusion research programs. In commercial and military equipments, the ignitron is applied as a d-c short-circuiting switch (or crowbar) across transmission lines to protect electronic components. The tube is also used in pulse modulator switching and electromagnetic and electrohydraulic metal forming.

This bulletin was prepared to supply the equipment designer information on these classes of service. It describes circuits that can be used and contains information on their design and construction. Basic theory and design of the ignitron as they relate to these services are also included. For easy reference, the Appendix contains a summary of mathematical equations included in the text.

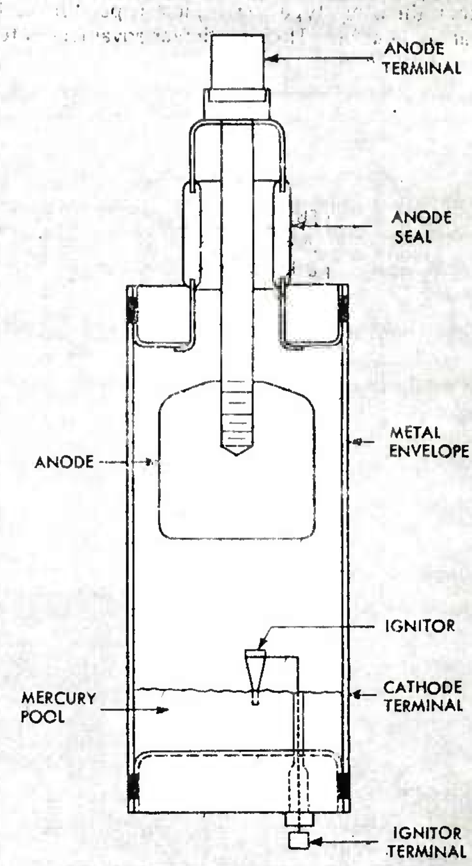


Fig. 1—Elementary Ignitron Without Baffles or Grids

PRINCIPLE OF OPERATION

The ignitron can be considered a switch with an ingenious closing device of unusual reliability and with almost indestructible electrodes. Fig. 1 shows a cutaway view of the elementary ignitron.

Without voltage on the ignitor, the device is, for practical purposes, an open switch capable of reliably withstanding high voltages without conduction of current.

When a forward voltage is applied between the ignitor and the mercury-pool cathode, the resistance between the two elements decreases suddenly from about 30 ohms to a few ohms as a hot spot forms on the interface between the mercury surface and the ignitor. Mercury vapor is generated and a mercury glow discharge forms between the ignitor and the spot. This discharge is sustained by the electrical energy from the ignitor voltage source. While this condition exists, the presence of a forward voltage in excess of approximately 15 volts from anode to cathode will cause ionized mercury vapor to fill the tube and allow conduction to occur. Since the voltage drop from anode to cathode is extremely low at this point, the tube can be considered a nearly perfect closed switch.

During conduction, the mercury-pool cathode provides an almost unlimited supply of electrons, making it an ideal switch for controlled capacitor discharges.

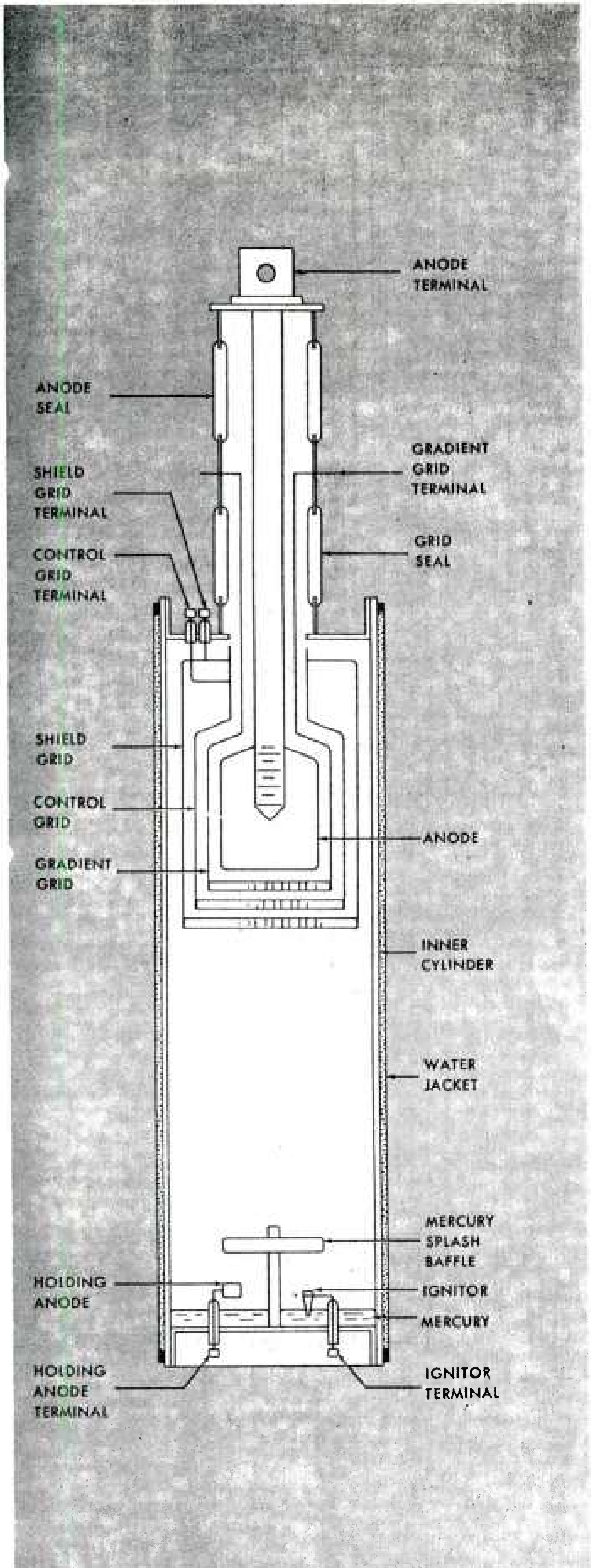


Fig. 2 — Ignitron with Holding Anode, Baffles and Grids.

For applications where circuit requirements exceed the capabilities of the elementary ignitron, other design features are utilized. Several such features are identified in Fig. 2.

The holding anode is used where the current may fall below the level required to maintain the cathode spot. A separate circuit providing current of more than ten amperes is applied from the holding anode to the cathode, thus maintaining the cathode spot.

For many repetitive operations, water cooling is used to stabilize ignition characteristics by maintaining proper temperatures and thus preventing internal vapor pressure buildup.

Where the voltage hold-off capability of the elementary ignitron is exceeded, electrodes in the form of baffles or grids can be inserted between the mercury pool and the anode. These grids, designated as the gradient electrodes, can be used as electrostatic shields or as voltage dividers.

For high repetition rates, a shield grid can be used as an aid to deionization.

A control grid can be utilized for low-jitter repetitive firing. In this sequence, ionization in the lower section of the ignitron is produced by ignitror firing. The electrostatic shielding between the anode and mercury pool is great enough to prevent voltage breakdown between them. When a positive signal voltage is applied to the control electrode, however, full ionization and voltage breakdown immediately follow.

CONSTRUCTION

Mercury, which provides the cathode and vapor for the ignitron, dictates choice of other tube materials.

The envelope is stainless steel, with glass insulators separating electrodes of different potentials. Fernico seals link the two materials. Anodes are usually graphite for unidirectional discharges or molybdenum or stainless steel for oscillatory discharges.

The ignitor is a boron carbide compound affixed to a carbon shank and supported by a molybdenum cross-arm. Because of choice of materials and preparation of ignitor surfaces, the ignitor does not wet to the mercury when pressed into the mercury surface. Instead, a downward mercury meniscus is formed, resulting in an interface of measurable resistance.

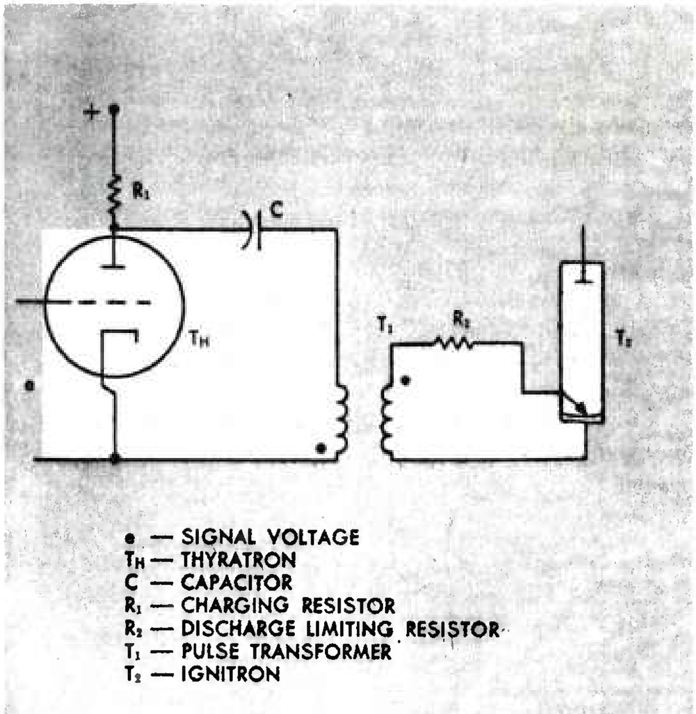


Fig. 3—Fundamental Ignitor Firing Circuit

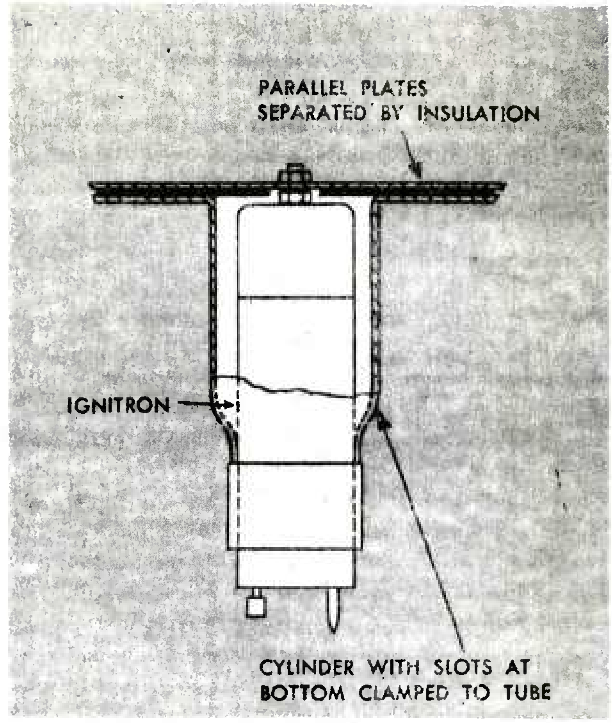


Fig. 4—Ignitron in Coaxial Mounting

OPERATION

The change from non-conducting to conducting state of the ignitron is initiated by the ignitor firing circuit —also called the ignitor excitation circuit.

For elementary ignitrons, the excitation circuit can be a single capacitor charged to several thousand volts and switched by a solid state device or a thyratron, as in Fig. 3. This circuit, in turn, can be triggered by a small signal. For a gridded ignitron, the excitation voltage is applied to the control grid and shield grid, as well as to the ignitor.

Once conduction is initiated, the current ideally would be carried in a symmetrical ionized mercury-vapor column. The column would extend from the cathode spot on the mercury-pool surface to a circular area on the anode. Since no device is absolutely symmetrical, no electrode surface perfectly uniform, and no external field without distortion, the actual column will have slight initial distortions.

As conduction of high current continues, the magnetic fields associated with the column and the current-conducting elements outside the tube will produce further distortion. As a result, the cathode spot will move from its original location and, in some milliseconds, will transfer from the mercury surface to the side walls. Time of transfer depends upon the magnitude of the distorting forces and the discharge current.

The dynamically unstable process of distortion will continue as the cathode spot moves up the side walls, shortening the length of the arc path. To minimize this distorting effect, a coaxial mounting (Fig. 4) is required for high-energy capacitor discharges.

In those industrial applications where current requirements are below 2000 amperes and 2000 volts, a single ignitron is used as a uni-directional switch. During conduction, excitation can be removed from the ignitor and conduction will continue until the voltage across the tube reverses. The ignitron will then cease to conduct and will hold off inverse voltage.

In capacitor-discharge and crowbar applications, applied voltages are often above 5000 volts and may be as high as 60,000 volts. Maximum discharge currents can be as great as 100,000 amperes per tube. Currents are initiated rapidly, rising from zero to maximum in microseconds. In these applications, the rapid rate of energy dissipation creates high temperatures on the electrodes. The tremendous currents leave a densely ionized vapor in the post-conduction period. With these conditions prevailing after initial conduction, the tube will not act as a uni-directional switch when inverse voltage is applied. Instead, it will conduct in the inverse direction as though it were a bi-directional switch. In applications where it is desired that oscillation continue, the ignitron can be used as a nearly ideal switch without further circuit modification. When reverse current cannot be tolerated, the addition of a second ignitron can eliminate reverse current through the load.

IGNITRONS IN CAPACITOR — DISCHARGE CIRCUITS

The behavior of the ignitron is dependent on the external circuit. Therefore, basic circuits and equations which describe the circuit parameters must be understood so the effects on the ignitrons can be predicted.

Fig. 5A shows a simplified discharge circuit. A d-c supply charges a capacitor in series with a charging resistor and a closed charging switch. The ignitron, in a non-ionized state, is an open switch. The charging switch is then opened and, when a discharge is required, a signal is applied to the ignitor excitation circuit. This converts the tube to a closed switch in less than a microsecond, permitting the capacitor bank to discharge through the load and the ignitron.

Voltages and current in the discharge loop can be analyzed by considering the equivalent circuit shown in Fig. 5B. The ignitron is represented in its bi-directional switching state.

The relationship of voltages, current and time are derived from the basic equation which describes the instantaneous voltage in any closed electrical circuit:

$$e_C + e_L + e_R = 0$$

where e_C is capacitor voltage
e_L is voltage across inductance
e_R is voltage across resistance

or:

$$E - \int \frac{i\,dt}{C} - L\frac{di}{dt} - iR = 0$$

where E is capacitor voltage
i is instantaneous current
t is time
C is capacitance
L is inductance
R is resistance

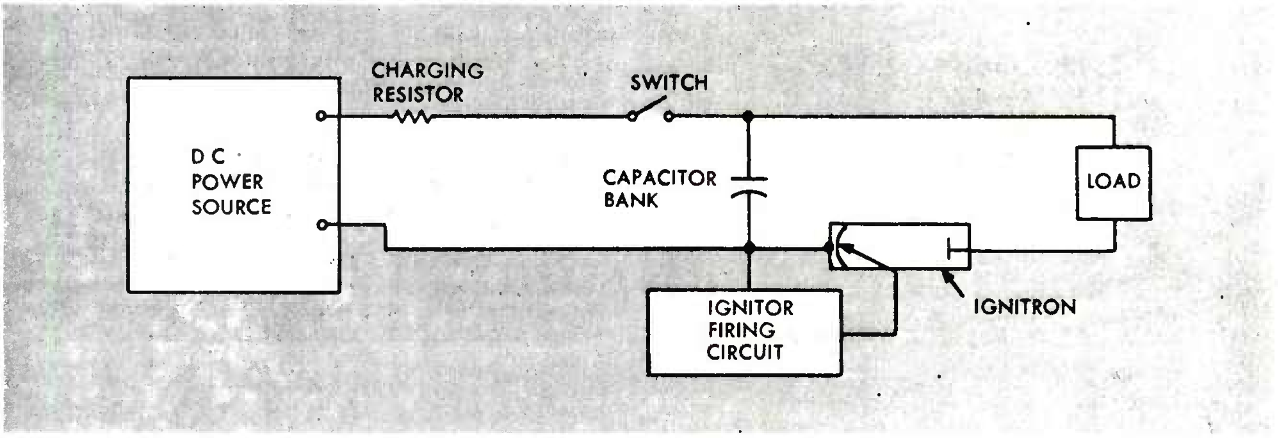


Fig. 5A—Simplified Capacitor-discharge Circuit

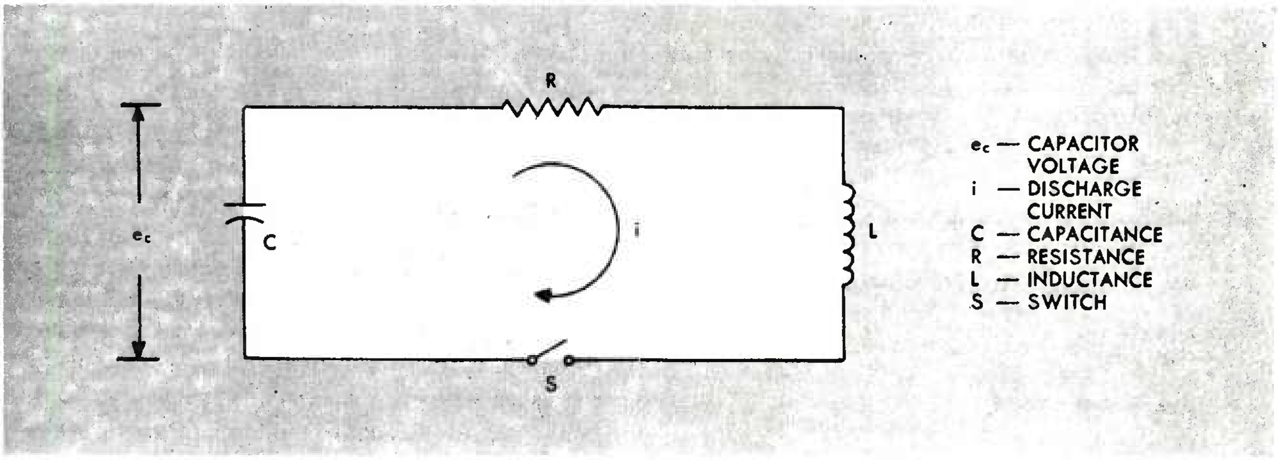


Fig. 5B—Equivalent Circuit for Capacitor-discharge Circuit

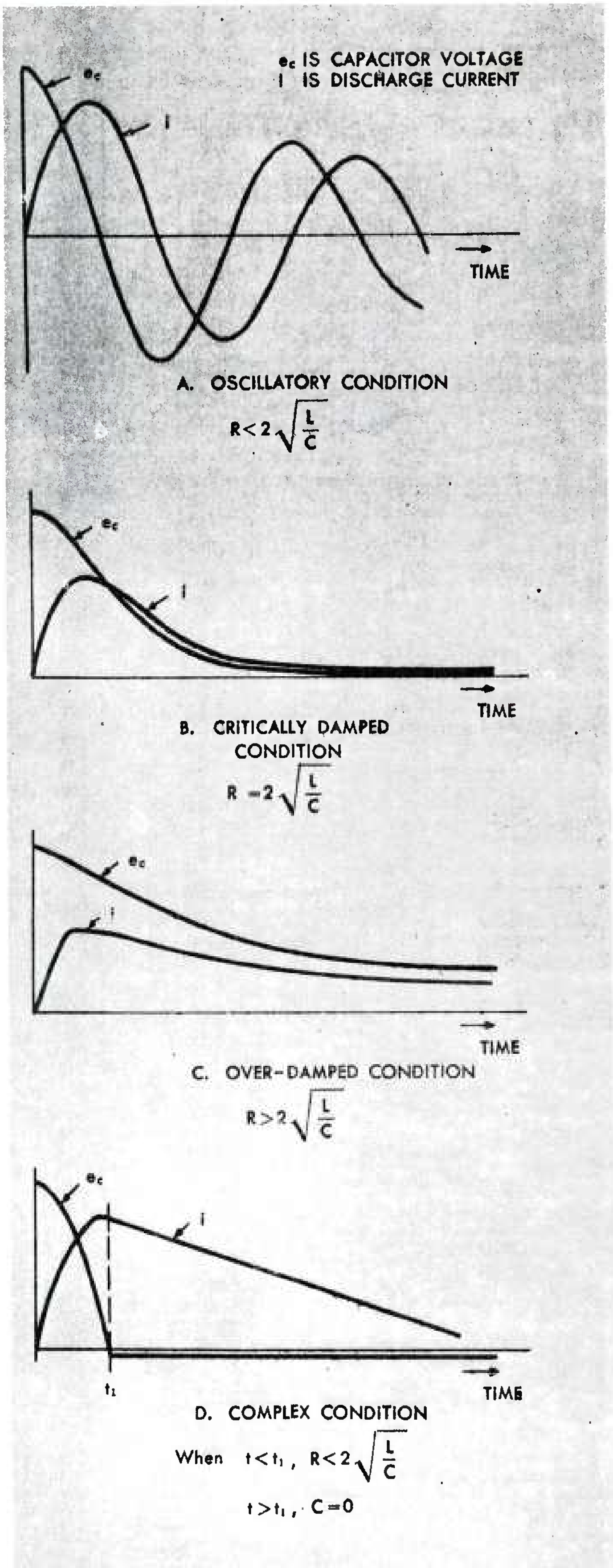


Fig. 6—Graphs of Voltage and Current Vs. Time in Series R-L-C Circuit

Three modes of operation can occur in a simple series circuit, depending on the relative magnitudes of resistance, inductance and capacitance in the discharge loop. A fourth mode can be produced by introducing a change in the circuit at an appropriate time during the discharge. These modes are shown in Fig. 6A through 6D where current and voltage variation versus time are represented.

The following equations assume circuit elements which retain constant characteristics for all excursions of current, voltage and frequency. Such conditions are not found in actual cases. For example, energy absorption in gases presents a decidedly nonlinear resistance to the circuit. Other common deviations can be anticipated. In the present state of the art, these departures from the ideal do not invalidate the use of the equations in the choice of ignitrons. Several useful relationships can be derived from the ideal equations by accepting judicious approximations.

The derivations of the equations which follow can be found in electrical engineering texts and handbooks.

The Oscillatory Condition $\left(R<2\sqrt{\frac{L}{C}}\right)$

For the oscillatory discharge which persists several cycles, it can be assumed that the discharge current and capacitor voltage vary sinusoidally.

From this assumption, the following equations can be derived:

Frequency:

$$f=\frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

where f is frequency (hertz)
L is inductance (henrys)
C is capacitance (farads)

$$\omega=\sqrt{\frac{1}{LC}}$$

where $\omega=2\pi f$ (radians per second)

$$f=\frac{1}{T}$$

where T is period of an oscillation (seconds)

Peak Current:

$$Cde=\left(\frac{2}{\pi}i_p\right)dt$$

where i_p is maximum current (amperes) during time, dt

$$i_p=1.57\,C\frac{de}{dt}$$

de is change in capacitor voltage (volts) during time, dt
dt is time for capacitor voltage to change from max. positive value to max. negative (seconds)

Inductance:

$$L = \frac{T^2}{4\pi^2 C}$$

Damping:

$$\frac{i_2}{i_1} = \varepsilon^{\left(-\frac{R}{2L}\right)\frac{T}{2}}$$

$$\frac{e_2}{e_1} = \varepsilon^{\left(-\frac{R}{2L}\right)\frac{T}{2}}$$

where i_1 is a maximum current occurring at time, t_1 (amperes)
i_2 is the next maximum current one-half cycle later (amperes)
ε is 2.72 (the base of the natural logarithmic system)
e_1 is maximum voltage occurring at time, t_1 (volts)
e_2 is maximum voltage occurring one-half cycle later (volts)

Percent Reversal:

$$\%\ \text{reversal} = \frac{e_2}{e_1}100$$

$$= \frac{i_2}{i_1}100$$

Resistance:

$$R = \frac{4L}{T} \ln \frac{e_1}{e_2}$$

where R is resistance (ohms)

Total Conduction:

$$Q_1 = \frac{1}{1-r}\left(\frac{T}{\pi}\right) i_p$$

where Q_1 is total charge through circuit during discharge (ampere-seconds)

r is $\frac{i_2}{i_1}$ or $\frac{e_2}{e_1}$

Approximate Time for Capacitor Voltage to Diminish to e_n:

$$t_n = \left[\frac{\ln \frac{e_1}{e_n}}{\ln \frac{e_1}{e_2}}\right] T$$

where e_n is voltage (volts) at time, t_n
t_n is time between e_1 and e_n

Application of Equations

To illustrate the use of these equations, the following exercise is presented.

A 100-microfarad capacitor is charged initially to 20,000 volts. A photograph, Fig. 7A, of the oscilloscope pattern during discharge is obtained with the apparatus represented in Fig. 7B.

From the above, frequency, peak current, inductance, percentage reversal, resistance and total conduction during discharge can be determined.

Frequency:

From Fig. 7A, the period of a full cycle is 200 microseconds.

$$f = \frac{1}{T}$$

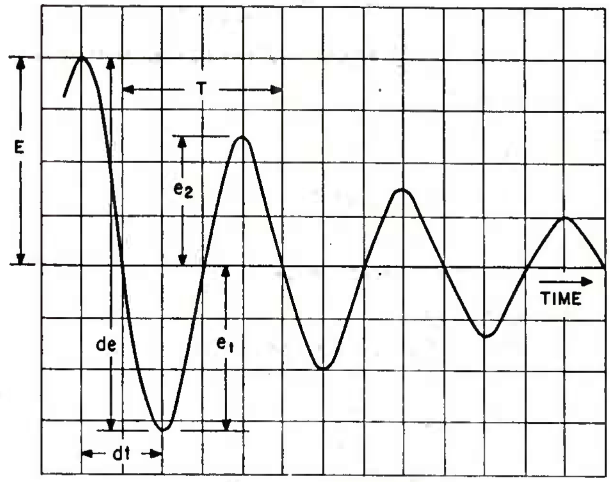


Fig. 7A—Oscilloscope Pattern from Capacitor-discharge Circuit

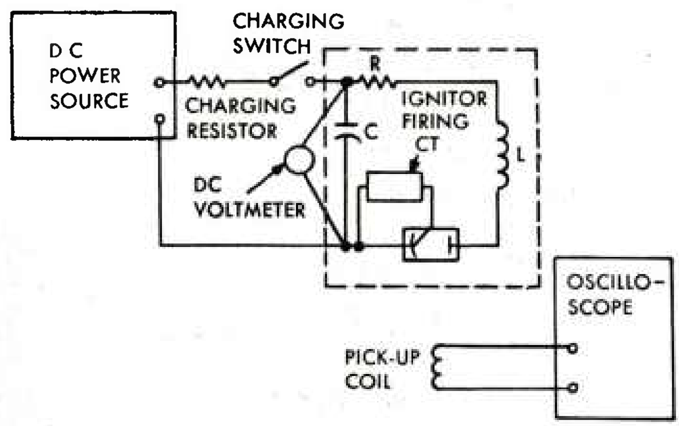


Fig. 7B—Method of Measuring Performance of Oscillatory Capacitor-discharge Circuit

$$= \frac{1}{200 \times 10^{-6}}$$

$$= 5{,}000 \text{ hertz}$$

Peak Current:

Since initial voltage was 20,000 volts and Fig. 7A indicated that the first peak is four divisions, the oscilloscope and camera can be considered calibrated to five kilovolts per division. The first maximum negative voltage is 3.2 divisions, hence:

$$de = 7.2 \text{ divisions} \times 5 \text{ kv per division}$$

$$= 36 \text{ kv}$$

$$dt = 100 \text{ microseconds}$$

$$i_p = 1.57\ C\ \frac{de}{dt}$$

$$= 1.57 \times 100 \times 10^{-6} \times \frac{36,000}{100 \times 10^{-6}}$$

$= 56,500$ **amperes (first maximum current)**

Inductance:

$$L = \frac{T^2}{4 \pi^2 C}$$

$$= \frac{(200 \times 10^{-6})^2}{4 \pi^2 \times 100 \times 10^{-6}}$$

$= 10.1$ **microhenrys**

Percent Reversal:

From Fig. 7A, e_1 is four divisions
e_2 is 3.2 divisions

$$\% \text{ reversal} = \frac{e_2}{e_1} 100$$

$$= \frac{3.2}{4 \times 100}$$

$$= 80\%$$

Resistance:

$$R = \frac{4L}{T} \ln \frac{e_1}{e_2}$$

$$= \frac{4 \times 10.1 \times 10^{-6}}{200 \times 10^{-6}} \ln \frac{1}{0.8}$$

$= 0.045$ **ohms**

Total Conduction:

$$Q = \frac{1}{1-r} \left(\frac{T}{\pi} \right) i_p$$

$$= \frac{1}{1-0.8} \left(\frac{200 \times 10^{-6}}{\pi} \right) 56,500$$

$= 18$ **ampere-seconds**

The Critically Damped Condition $\left(R = 2\sqrt{\frac{L}{C}} \right)$

When the critically damped condition prevails, the discharge current does not reverse direction as in the oscillatory case. Instead a maximum current is reached at an earlier time. The current then diminishes rapidly at a rate determined by the ratio of the circuit constants. In many applications, a critically damped discharge is desired to avoid current reversal and to complete the discharge in minimum time. The following relationships are useful.

Peak Current:

$i_p = 0.736 \frac{E}{R}$ **where** i_p is maximum current (amperes)
E is voltage on capacitor prior to discharge (volts)
R is resistance (ohms)

Capacitor Voltage when Current Peaks:

$e_C = 0.736\, E$ **where** e_C is capacitor voltage (volts)

Time to Reach Peak Current:

$t_p = \frac{2L}{R}$ **where** t_p is time (seconds)
L is inductance (henrys)
C is capacitance (farads)

$$= \frac{RC}{2}$$

Inductance:

$$L = \frac{R^2 C}{4}$$

$$= \frac{t_p^2}{C}$$

Resistance:

$$R = \frac{2t_p}{C}$$

Capacitance:

$$C = \frac{4L}{R^2}$$

$$= \frac{2t_p}{R}$$

Charge:

$Q = CE$ **where** Q is total charge through circuit (ampere-seconds)

When a critically damped discharge is required, the problem is to achieve the proper circuit constants to insure the critical relationship.

The discharge current form can be measured at low voltage and current with an oscilloscope across a series non-inductive viewing resistance, or with an oscilloscope and pick-up coil (Fig. 7B) with a suitable resistance-capacitance integrating circuit. The capacitor voltage can be viewed with a capacitor divider and oscilloscope. The use of the equations above are illustrated in the following example.

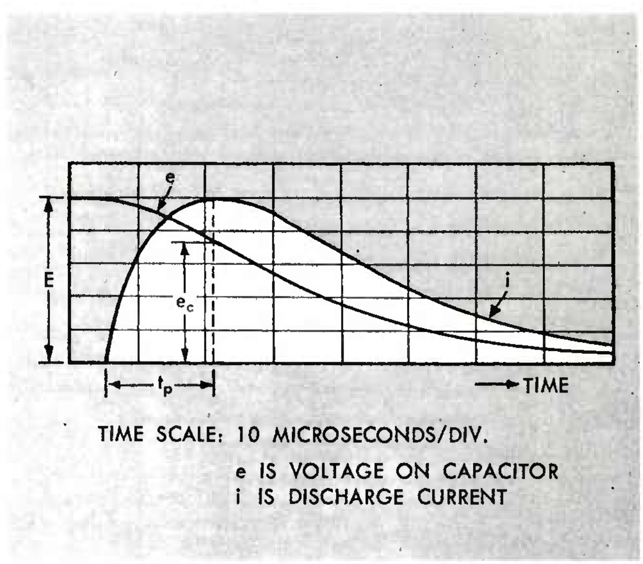


Fig. 8—Oscilloscope Patterns of Current and Capacitor Voltage in Critically Damped Discharge

Application of Equations

A capacitor-discharge circuit with a 100-microfarad capacitor is initially charged to 20,000 volts. A photograph of patterns of current and capacitor voltage (Fig. 8) is taken during discharge with 2000 volts initially on the capacitor.

Peak current, inductance, resistance, charge and verification of critical damping can be determined.

Peak Current:

$$i_p = 0.736 \frac{E}{R}$$

$$= 0.736 \times \frac{20{,}000}{0.64} \quad \text{(Resistance computed below)}$$

$$= 23{,}000 \text{ amperes}$$

Inductance:

$$L = \frac{t_p^2}{C}$$

$$= \frac{(32 \times 10^{-6})^2}{100 \times 10^{-6}}$$

$$= 10.2 \text{ microhenrys}$$

Resistance:

From Fig. 8, the time to reach maximum current is measured as 32 microseconds.

$$R = \frac{2t_p}{C}$$

$$= \frac{2\,(32 \times 10^{-6})}{100 \times 10^{-6}}$$

$$= 0.64 \text{ ohms}$$

Charge:

$$Q = CE$$

$$= 100 \times 10^{-6} \times 20{,}000$$

$$= 2.0 \text{ ampere-seconds}$$

Verify Critical Damping:

The amplitude of voltage at the time, t_p, is measured as 5.9 divisions.

Amplitude at zero time is measured as eight divisions.

$$e_C = 0.736\ E$$

$$5.9 = 0.736 \times 8$$

The circuit must be critically damped. If an over-damped condition existed, e_C would be greater than 0.736 E at the time of current maximum. If an oscillatory condition were being approached, the voltage trace would be at or near zero at peak current.

The Over-damped Condition $\left(R > 2\sqrt{\frac{L}{C}}\right)$

The over-damped discharge reaches its peak current earlier than the other conditions, but maximum current amplitude is lower. Duration of currents near the highest level and significant capacitor voltage persist longer than for the critically damped condition.

The following fundamental relations are presented.

Current:

$$i = \frac{E\varepsilon^{\left(\frac{-Rt}{2L}\right)}}{NL} \sinh Nt$$

where i is instantaneous current (amperes)

E is initial voltage on capacitor (volts)

ε is 2.72 (the base of the natural logarithmic system)

R is resistance (ohms)

L is inductance (henrys)

C is capacitance (farads)

$$N = \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$$

Voltage:

$$e_C = E\varepsilon^{\left(\frac{-Rt}{2L}\right)} \left(\cosh Nt - \frac{1}{N} \sinh Nt\right)$$

where e_C is instantaneous voltage on capacitor (volts)

Time of Current Maximum:

$$t_p = \frac{1}{N} \tanh^{-1} \frac{2NL}{R}$$

where t_p is time for current to reach maximum (seconds)

The numerical computations are unwieldy but can be performed by direct substitution in the equations above. Tables of hyperbolic functions are available in handbooks and textbooks.

The extreme over-damped condition occurs when resistance is far greater than the critical damping resistance. The discharge is then described by equations derived from analysis of the simple resistance-capacitance series circuit with peak current occurring almost instantaneously on triggering. Some useful relationships are summarized here.

Peak current:

$$I = \frac{E}{R}$$

where **I** is initial and maximum current (amperes)

E is initial voltage on the capacitor (volts)

R is circuit resistance (ohms)

Current:

$$i = I\varepsilon^{\frac{-t}{RC}}$$

where **i** is current at time, t (amperes)

ε is the number, 2.72 (the base of the natural logarithmic system)

C is capacitance (farads)

Capacitor voltage:

$$e_C = E\varepsilon^{\frac{-t}{RC}}$$

where e_C is capacitor voltage (volts) at time, t

Time constant:

$$t_C = RC$$

where t_C is time for current and voltage to decrease to 0.369 of magnitude at any instant (seconds)

Charge:

$$Q = CE$$

where **Q** is total charge through circuit (ampere seconds)

The Complex Condition

When the work to be done dictates a circuit which will inherently oscillate but where the current reversal is not permissible, the strategy of Fig. 9 is used to achieve the discharge current of Fig. 6D. The sequence of events is shown in Fig. 10.

When the series ignitron is fired, a sinusoidal current occurs. Its characteristics are fixed by the circuit constants as discussed for the oscillatory case. As current begins to fall from peak value and capacitor voltage is almost zero, all the energy initially on the capacitor which has not yet been dissipated will reside in the magnetic field of the inductive load. When the voltage becomes zero, the crowbar ignitron is fired. The energy of the system stored in the magnetic field will be returned as uni-directional current in the circuit comprised of the crowbar tube and load.

In an ideal circuit with no stray inductance or capacitance, the crowbar current can be expressed as:

$$i = I\varepsilon^{\frac{-Rt}{L}}$$

where **i** is instantaneous current (amperes)

I is current at instant of crowbarring (amperes)

R is resistance (ohms)

ε is 2.72 (the base of the natural logarithmic system)

t is time after crowbarring begins (seconds)

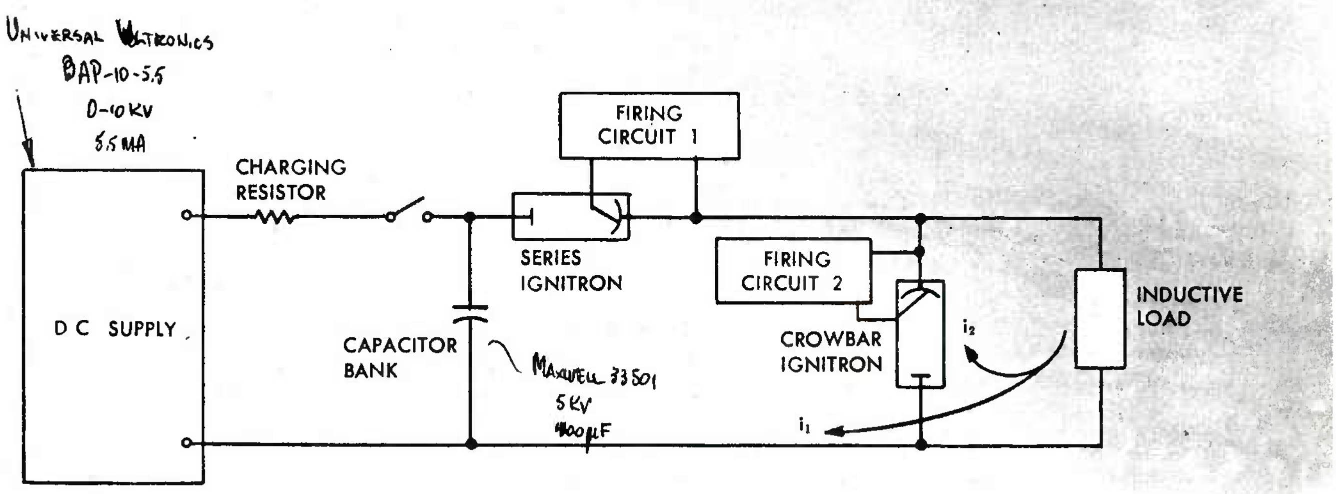
L is crowbar circuit inductance (henrys)

This is the description of a simple decaying current. However, stray reactive components cause the oscillations shown in Fig. 10.

The charge conducted by the crowbar ignitron can be expressed as:

$$Q = \frac{L}{R} I$$

where **Q** is the charge conducted by the crowbar ignitron (ampere seconds)



BOTH IGNITRONS = MAXWELL No. 95-00865

Fig. 9—Oscillatory Discharge Circuit with Ignitron Crowbar

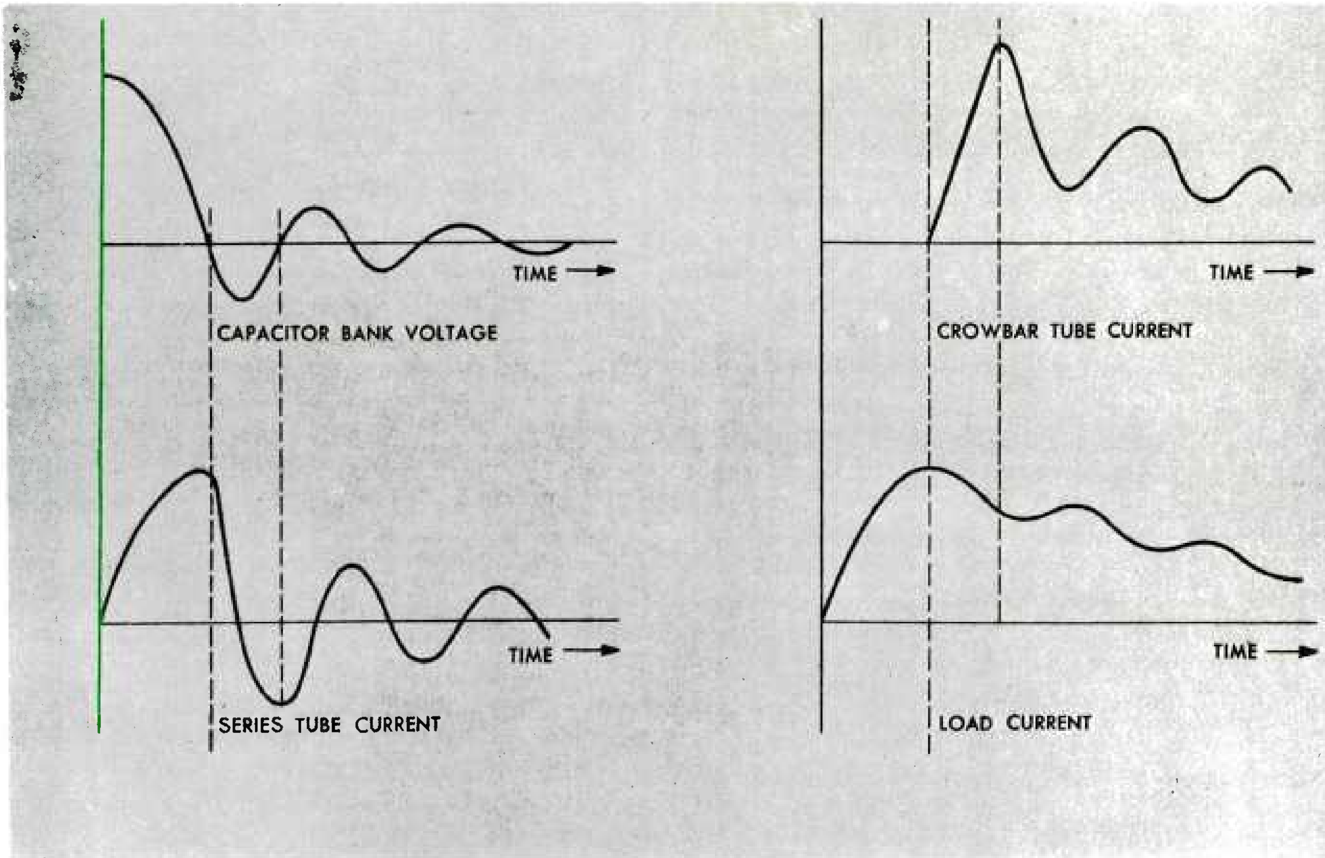


Fig. 10—Capacitor Voltage and Currents in Complex Discharge Circuit

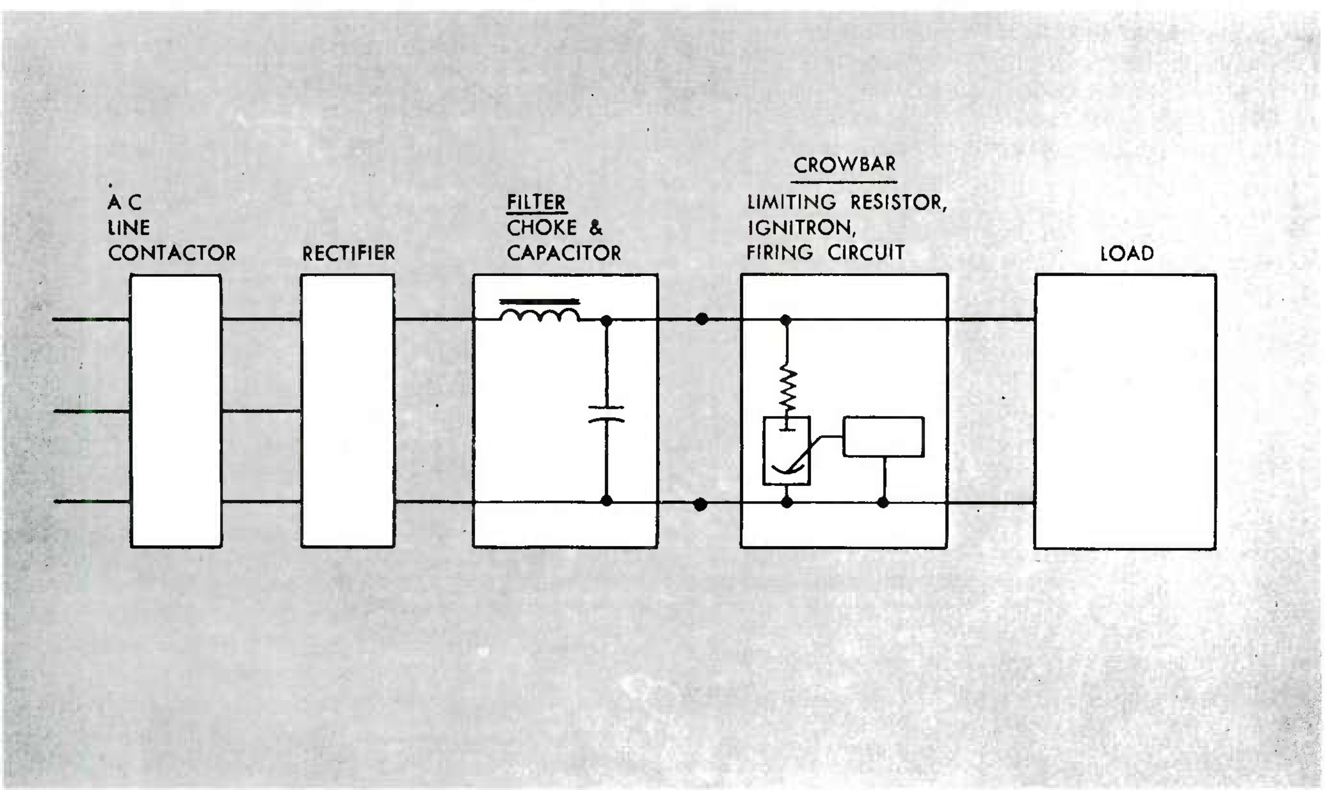


Fig. 11—The Ignitron in DC Short-circuiting (Crowbar) Service

IGNITRONS IN CROWBAR SERVICE

Large high-voltage, high-power equipment must be protected against damage caused by momentary fault, which would result in excessively high short-circuit currents. Permanent damage in the equipment can occur before high-speed circuit breakers can open.

The present best protective device is a d-c short circuit across the power supply terminals which diverts power supply energy from the fault. An ignitron at the power supply terminals, triggered to its ionized state in less than a microsecond, is an ideal device for this crowbar service. The load is protected until circuit breakers remove the input power from the system. A block diagram of such a system is shown in Fig. 11.

The ignitron in series with an appropriate resistor is triggered from the nonconductive to the conducting state when a fault-sensing element in the system delivers its signal to the ignitor firing circuit. The ignitron, acting as a switch, conducts a current similar to that in Fig. 12. During period t_1, the crowbar current is a critically damped discharge. The equivalent circuit could be that of Fig. 5B with a filter capacitor of the power supply as the capacitance, and the stray inductance of the wiring and components as the inductance. The resistance may be a component inserted so that circuit resistance creates critical damping.

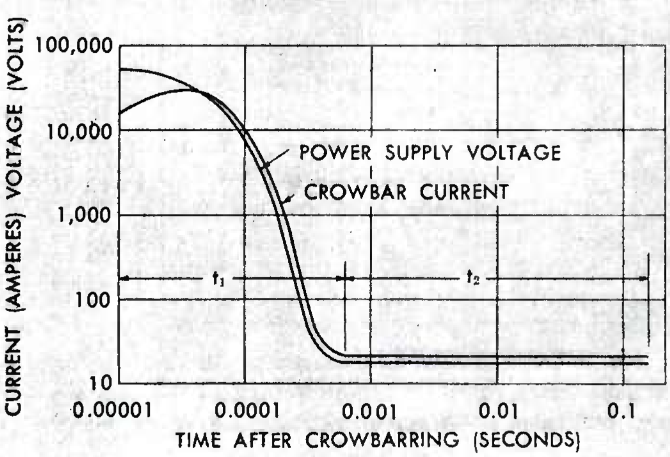


Fig. 12—Crowbar Current and Power Supply Voltage Vs. Time

The discharge almost goes to completion in tens to hundreds of microseconds. The process of capacitor discharge is so rapid that the rectifier is effectively isolated from the crowbar during this initial period by the filter choke. However, as the crowbarring continues, the rectifier delivers full short-circuit current through the crowbar until the a-c contactors open.

An auxiliary anode current of over ten amperes may be required to maintain the ignitron in an ionized state if the crowbar current approaches zero in the interval when the power supply filter capacitor is nearly discharged — but before the power supply short circuit current rises to this level.

For some systems, it is possible to insert the limiting resistor in series with a power supply steady-state current. When crowbarring occurs, the fault voltage will fall to zero immediately upon ignitor firing.

IGNITRON CHARACTERISTICS

Voltage Ratings

Peak forward voltage is the maximum positive voltage that can be applied from anode to cathode without causing tube conduction prior to ignitor firing.

Peak inverse voltage is the maximum negative voltage that can be applied from anode to cathode without causing tube conduction prior to ignitor firing.

Critical anode starting voltage is the minimum positive anode voltage at which tube conduction will begin when ignitor firing occurs.

Recovery Time

Recovery time is the interval following discharge which must elapse before positive voltage can be applied to the tube. Present ignitron ratings do not specify a recovery time. Notes on the rating sheet do caution that, after discharge at full rating, a one- to ten-second delay may be required before re-application of anode voltage.

This delay assures that deionization of the mercury vapor has approached completion and that internal tube temperatures have approached the ambient temperature. Quantitative prediction of recovery requires specific knowledge of the rate of discharge, energy discharged, duration and nature of discharge current pulse, voltage re-application rate, and type of cooling.

Current Ratings

Published G-E ratings for elementary ignitrons represent evaluation tests conducted by the Atomic Energy Commission and by General Electric at peak rated voltage. The gridded ignitrons are at present rated on their past performance in military and industrial systems.

In the capacitor-discharge current ratings for one elementary ignitron, a test condition is a damped oscillatory discharge with a frequency of 2500 cycles per second. described as a half-sine wave of 120 microsecond base. The first current maximum in the oscillatory train is 60,000 amperes. The damped oscillations persist for 20 cycles.

The second test condition is an oscillatory frequency of 25,000 cycles per second (half-sine wave base of 20 microseconds) persisting for 20 cycles with the maximum current of 100,000 amperes.

In crowbar service, a non-oscillatory discharge is defined. This current should degenerate to less than 100 amperes within two milliseconds. The d-c short-circuit current beyond this time should persist no longer than a tenth of a second. These approximate values are proposed to prevent damage to the tube which would result from a prolonged d-c current when the cathode spot is anchored to the side wall of the tube.

For d-c short-circuiting application where currents are greater than 50 amperes, it is recommended that the input to the d-c supply be equipped with high-speed circuit breakers which will limit the duration of the short-circuit current to about 30 milliseconds.

Though not in the present rating system, tests have established the capability of the elementary ignitrons to conduct approximately 30 ampere-seconds of charge with good recovery characteristics. As further tests extend this tentative limit, published data will be revised to include the information.

Total Charge

The total charge through the ignitron can be computed for the specific circuit under consideration. For oscillatory circuits, the charge involved in successive reversals should be considered, as shown in the total-conduction example on page 10. In energy-diverter (power-supply crowbar) service, the charge conducted until contact or opening should not be ignored.

Discharge Rate

A maximum discharge rate for the elementary ignitrons is based upon the maximum voltages and currents being applied during the conditions described in the paragraph defining current ratings. Applications must be analyzed before a maximum discharge rate can be estimated. In many instances, higher rates than the maximum specified are permissible. As repetition rates exceed elementary design capabilities, high-rep-rate ignitrons should be used.

Tube Inductance

When a coaxial mounting is used, the inductance of the elementary ignitron is approximately 0.04 microhenrys. Most circuits include much greater inductances in wiring and other components, making the effect of tube inductance negligible.

Tube Resistance

Tube resistance during discharges of several thousand amperes has been estimated at less than 10 milliohms. In most applications, this resistance is negligible compared to circuit and load resistance.

Ionization Time

The ionization time is the time required after application of ignitor excitation for anode conduction to be established. For minimum ionization time, the ignitor firing circuit should have a rise time of less than one-half microsecond and should have an open circuit voltage of at least 2000 volts. Ionization is readily attained with lower voltages and currents. However, the lower level of excitation results in longer ionization times and greater disparity from pulse to pulse in ionization times.

With the recommended ignitor excitation, cathode-spot formation time is approximately 0.5 microseconds, and tube conduction follows in approximately 0.1 microsecond under normal operating conditions.

Life

The number of shots expected from an ignitron in a specific service is dependent on several circuit conditions acting simultaneously. In general, life varies inversely as the cube of the peak current and inversely as the square of the current duration. An analytical

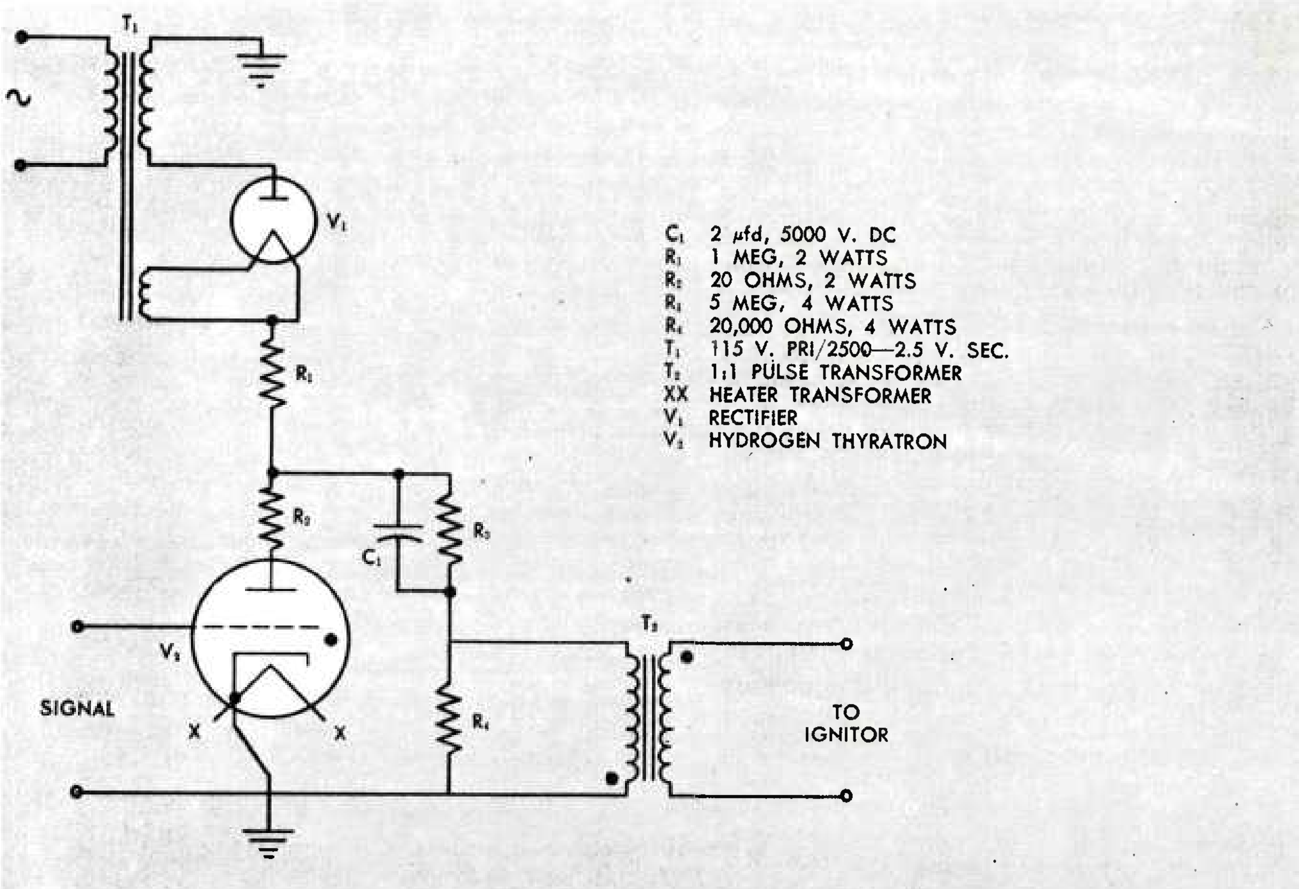


Fig. 13—Ignitor Firing Circuit

expression yielding precise predictions is not available. Best predictions are still made by comparison with similar applications.

Ignitor Requirements

The ignitor excitation circuits should be evaluated separately from the ignitron, and published data refer to circuit parameters obtained in this manner.

Open-circuit Voltage

Ignitor open-circuit voltage is measured at the firing circuit output terminals with ignitor disconnected.

Short-circuit Current

The short-circuit current rating is for the ignitor circuit alone when its terminals are short-circuited. Short-circuit current may be as low as 50 amperes and it is likely that further development of circuitry will reduce the published requirements. The ultimate limit will be that minimum excitation level at which reliable firing is still obtained.

It is good practice to maintain a cathode spot by ignitor excitation during the entire capacitor discharge. The energy required to maintain a cathode spot is small. Applicable is the capacitor-discharge type of excitation which provides high voltage initially, but which will still provide sufficient voltage and current later in the main discharge to maintain a cathode spot. Such a circuit, adequate for initiating capacitor discharges and d-c short-circuiting switching in many applications, is shown in Fig. 13. Similar circuits using SCR's have also been developed.

For gridded ignitrons, where signals must be applied to the ignitor and grids, more complex circuitry is required.

Mounting Methods

Mounting methods will differ from application to application. However, the vertical anode-terminal-up position recommended in published data and the coaxial return are all provided by the cathode mount detailed in Fig. 14 for the small ignitron. Fig. 15 shows a typical coaxial mount for gridded ignitrons.

Type of Cooling

For best performance, the mercury pool of the ignitron should be kept below 40 C and should be several degrees cooler than the anode. When the cathode temperatures become greater, voltage hold-off ability and recovery properties are temporarily decreased. For high-duty applications of small ignitrons, additional cathode cooling may be required in the forms of air directed at the cathode or water coils brazed to the coaxial mount as indicated in Fig. 14.

The gridded ignitron, whose construction provides the high voltage hold-off capability, also has firing requirements more exacting than those of the elementary tubes. To maintain the optimum internal tube temperatures for reliable starting, a water jacket is incorporated in the tube. Water temperature should be maintained at about 35 C. Anode temperature is maintained at about 75 C by radiant heat if the ignitron is to be used near its maximum voltage ratings.

Conditioning Schedule

For an ignitron to perform reliably at high voltage, no residual gas should be present in the tube and no mercury can be tolerated on the internal surface of the anode seal. This seal is part of the tube envelope and electrically separates cathode from anode.

To assure that newly shipped tubes conform to both

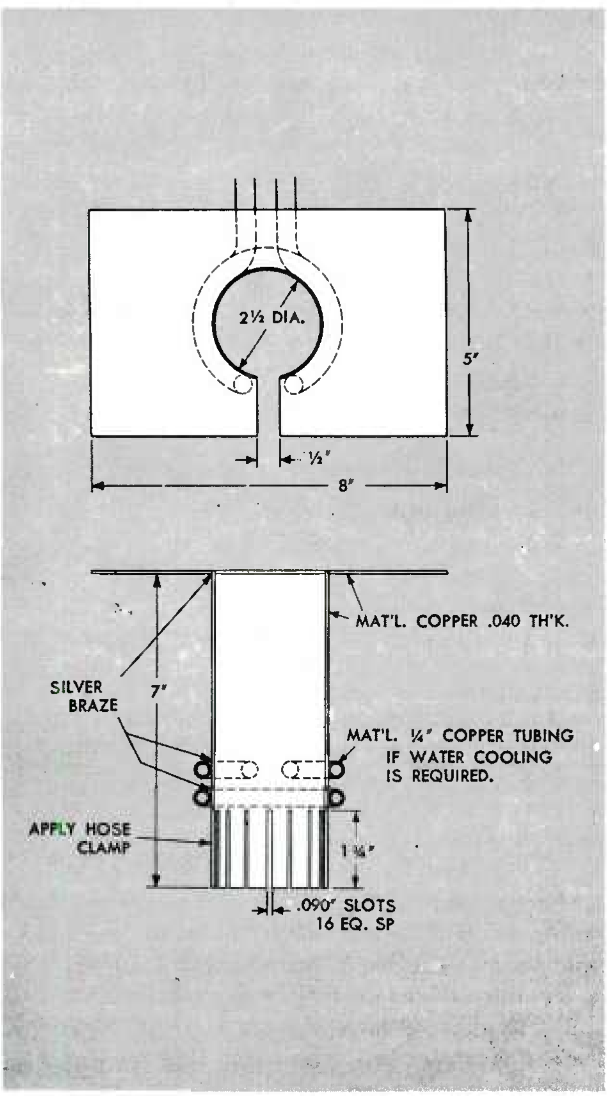


Fig. 14 — Coaxial Mount for Elementary Ignitron

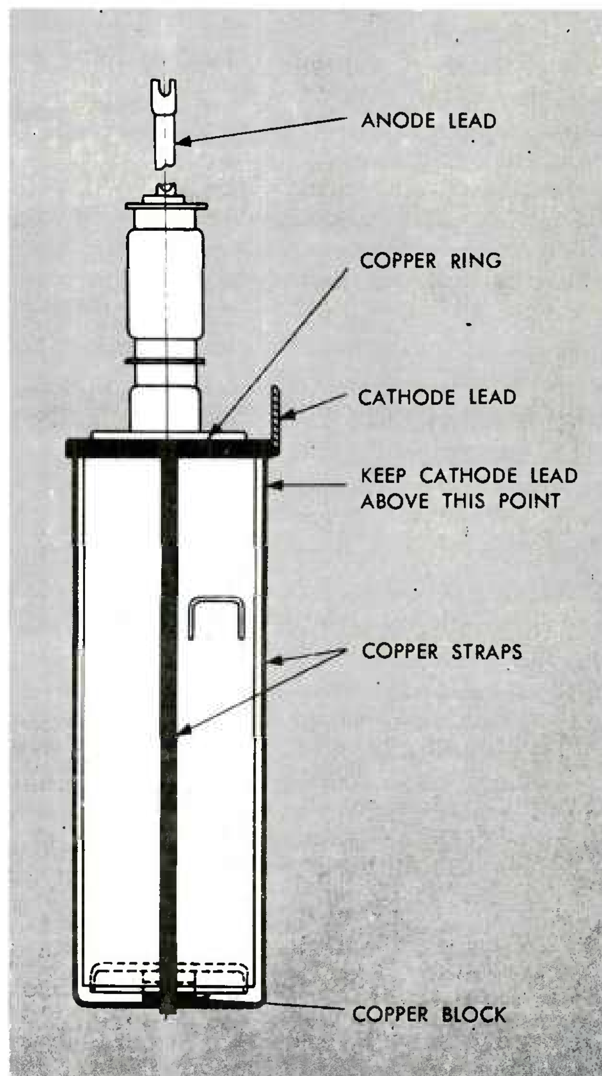


Fig. 15 — Coaxial Cathode Return for Gridded Ignitron

requirements, the following conditioning schedule is suggested prior to tube use.

First, direct a 100-watt heat lamp at the anode lead and seal area for several hours. The temperature differential thus set up in the tube will distill the mercury in the anode region to the cathode end.

Second, keep the tube in a vertical position during subsequent handling.

Next, subject the tube to a high-potential test. An a-c or d-c potential is applied from anode to the cathode with current flow limited to 5 to 50 milliamperes. Intermittent conduction can be detected with a milliammeter or with a neon glow lamp connected across an appropriate part of the series limiting resistance.

Raise the voltage slowly. Occasional voltage breakdowns may occur, resulting in conduction. However, in a good tube, conduction periods will be intermittent and will last for only a fraction of a second. If current tends to become continuous, voltage must be quickly reduced until current ceases. Increased voltage may then be re-applied. In this manner, it will be possible to apply a few kilovolts above the tube ratings in approximately an hour.

Handling Practice

Once the conditioning has been completed, it need not be repeated unless mercury again comes in contact with the anode seal.

During standby, the anode should be kept at a slightly higher temperature than the cathode. Radiant heat directed at the anode prior to operation after long standby will assure good tube performance.

Installation

When installing elementary ignitrons in the coaxial mounting, connect the anode first. Apply torque only between the hexagonal nut at the base of the anode stud and a nut threaded on the anode stud. Torque applied by holding the body of the tube while tightening the anode nut could break the anode seal.

Line up the coaxial cylinder with the axis of the tube before tightening the clamp around the cathode. Misalignment could result in tube damage.

Use a small amount of clean grease on the stainless-steel contact surfaces to prevent deterioration of the electrical contact between the tube and clamp.

Request the appropriate ignitor lead when ordering the tube. Leads are available in 7¾-inch and 13½-inch lengths, and fit ignitrons with 0.250-inch diameter ignitor terminals. The lead has a cap which engages the ignitor stud at one end and terminates in a lug at the other end for connection to firing circuitry.

Residual Voltage

In oscillatory discharges, the energy on the capacitor will never be entirely dissipated in the load. As the voltage amplitude of the oscillation becomes smaller, the ignitron will successfully hold off a small inverse voltage. This leaves the capacitor bank with a residual charge in direction opposite to its original charge. In many installations, circuits are provided to completely discharge the bank after regular discharge ends.

SERIES AND MULTIPLE OPERATION

When the capabilities of an individual ignitron are exceeded, ignitrons can be used in combination to meet the requirements.

If the hold-off voltage requirements exceed the ratings of a single ignitron, the tubes may be arranged for 16(a). series operation. Such a circuit is shown in Fig. ~~16~~. The ionization time for the series arrangement is twice the ionization time of a single ignitron, or about one to two microseconds. If this delay is not tolerable 16(b), a second firing circuit, as shown in Fig. ~~17~~ could be provided for ignitron V_1 so that ionization in both tubes could occur simultaneously.

The large gridded ignitrons have been successfully used in series operation.

In many applications the current capacity of a single ignitron is exceeded. In some of the Atomic Energy Commission installations where megajoules of charge are being switched, hundreds of small ignitrons are fired simultaneously so that no single tube in the parallel bank is over-stressed.

The tube arrangement is one of simple paralleling with a single firing circuit for banks of eight to 16 switch tubes. The principle is shown in Fig. 17.

For ideal operation, each branch of the parallel circuit should contain some inductance. The presence of this inductance during firing assures adequate anode voltage across a tube which ionizes an instant later than other tubes. In some circuits, the length of leads is sufficient to provide adequate isolation between tubes and assures adequate firing voltages for late-firing tubes. In other circuits, each tube is in series with part of the capacitor-discharge bank so that it is partly isolated from other tubes during ionization.

CHOOSING THE APPROPRIATE TUBE

Each application will involve individual considerations. The exercise below is presented as an example of the reasoning which would lead to the choice of a combination of ignitrons for a specific task.

A capacitor is charged to 18 kv initially in a circuit which will have an estimated reversal of 85 percent at a frequency of 15,000 hertz, and an initial peak current of 118,000 amperes. Frequency of operation will be once every two minutes.

The task requires a voltage hold-off capability of 18 kv. From Table I (page 2), an elementary ignitron with a 20-kv peak anode voltage rating may be considered.

118,000 amperes is beyond the peak current capability of a single elementary tube. Hence two tubes in parallel should be considered.

Total charge per tube should be checked.

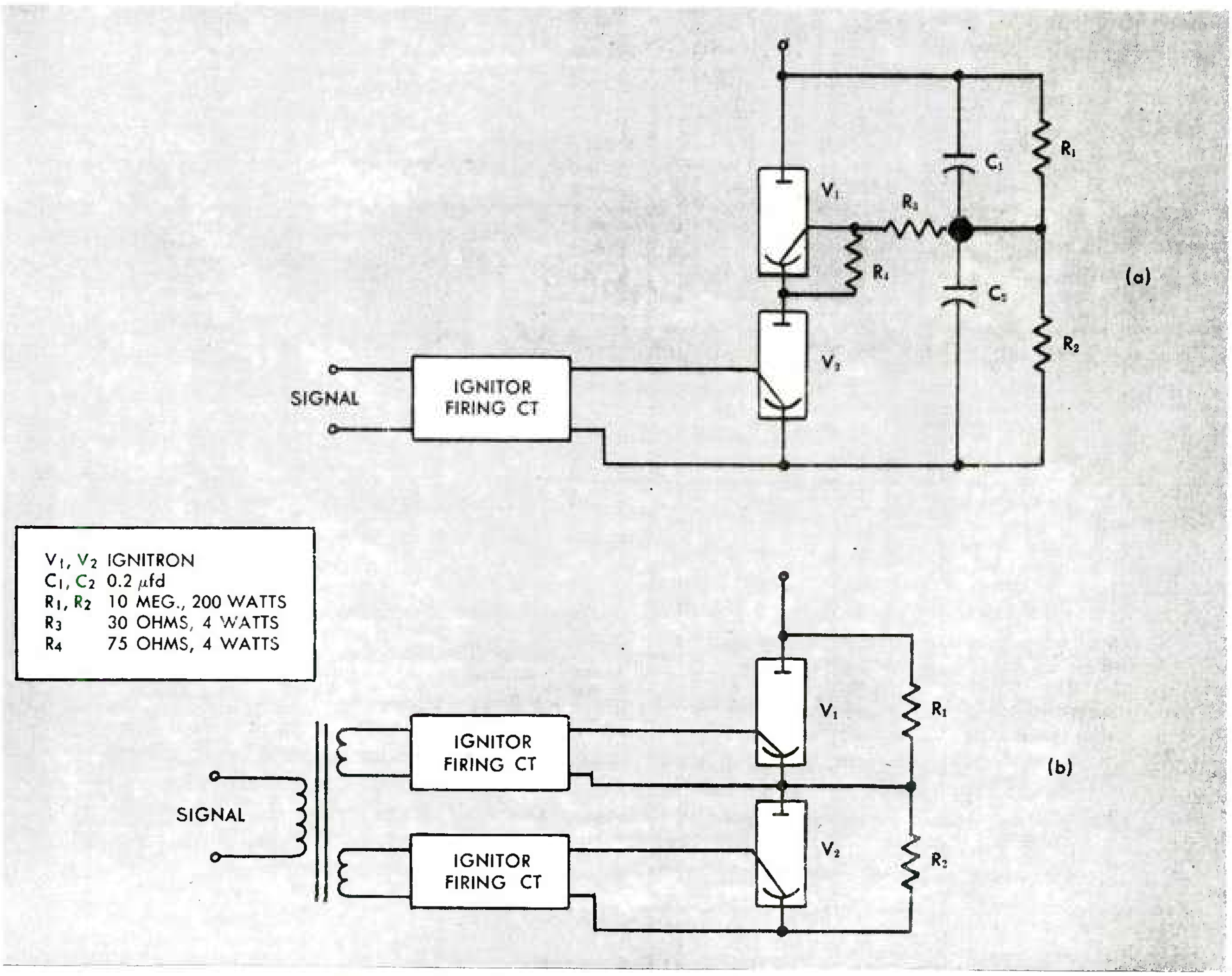


Fig. 16—Series Operation of Ignitrons to Control High-Voltage Discharge

$$\text{Total Charge} = \frac{1}{1-r}\left(\frac{T}{\pi}\right) i_p \quad \text{where } r = .85$$

$$T = \frac{1}{f} = 66.6 \times 10^{-6}$$

$$i_p = 59{,}000 \text{ amperes/tube}$$

$$= \frac{1}{1-.85}\left(\frac{66.6 \times 10^{-6}}{\pi}\right) 59{,}000$$

$$= 8.35 \text{ ampere-seconds/tube}$$

This is well within the recommended limits.

Duration of discharge should also be checked. The assumption could be made that conduction ceases when inverse voltage becomes less than 1000 volts.

$$t_n = \left[\frac{\ln\left(\frac{e_1}{e_n}\right)}{\ln\left(\frac{e_1}{e_2}\right)}\right] T \qquad \text{where } e_1 = 18000,\; e_2 = 0.85\, e_1,\; e_n = 1000$$

$$= \left[\frac{\ln\left(\frac{18000}{1000}\right)}{\ln\left(\frac{18000}{0.85 \times 18000}\right)}\right] 66.7 \times 10^{-6}$$

$$= 1178 \text{ microseconds}$$

This pulse duration is within recommended limits.

Finally, frequency of operation should be checked. This is within specified limits.

The choice of two elementary ignitrons rated for peak anode voltage of 20 kv and peak current of 100,000 amperes is conservative. Tubes should provide many thousands of successful operations.

The selection of the proper ignitron for a capacitor-discharge or crowbar application follows a survey of all circuit conditions such as peak voltage, maximum current, duration and nature of discharge, and frequency of discharge as well as the reliability and life required of the apparatus and its physical limitations. This bulletin is a summary of principles and practice involved in the use of ignitrons for capacitor-discharge and crowbar applications. For broader, more definitive studies, several excellent detailed articles can be consulted. To make this information more readily available, a bibliography is included.

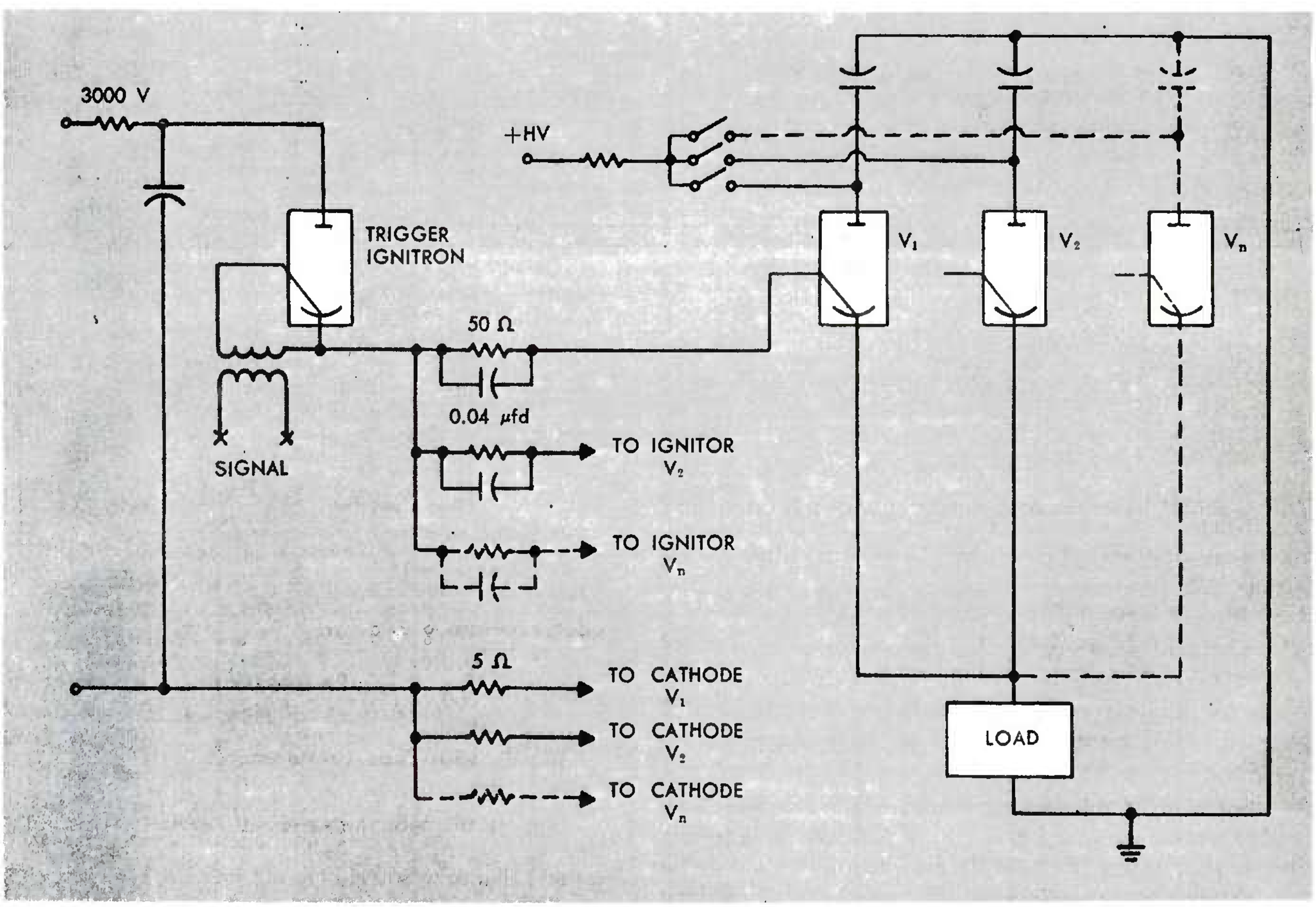


Fig. 17—Parallel Operation of Ignitrons with Single Firing Circuit

APPENDIX

SUMMARY OF EQUATIONS

THE OSCILLATORY CONDITION: $R < 2\sqrt{\frac{L}{C}}$

Frequency: $f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$

$$\omega = \sqrt{\frac{1}{LC}}$$

$$f = \frac{1}{T}$$

Peak Current: $Cde = \left(\frac{2}{\pi} i_p\right) dt$

$$i_p = 1.57\ C\frac{de}{dt}$$

Inductance: $L = \frac{T^2}{4\pi^2 C}$

Damping: $\frac{i_2}{i_1} = \frac{e_2}{e_1} = \mathcal{E}^{\left(\frac{-R}{2L}\right)\frac{T}{2}}$

Percent Reversal: $\%\ \text{reversal} = \frac{e_2}{e_1}\,100$

$$= \frac{i_2}{i_1}\,100$$

Resistance: $R = \frac{4L}{T}\ln\frac{e_1}{e_2}$

Total Conduction: $Q_1 = \frac{1}{1\text{-}r}\left(\frac{T}{\pi}\right) i_p$

Approximate time for capacitor voltage to diminish to e_n: $t_n = \left[\frac{\ln\frac{e_1}{e_n}}{\ln\frac{e_1}{e_2}}\right] T$

THE CRITICALLY DAMPED CONDITION: $R = 2\sqrt{\frac{L}{C}}$

Peak Current: $i_p = 0.736\frac{E}{R}$

Cap. Volt. at i_p: $e_C = 0.736\ E$

Time to reach i_p: $t_p = \frac{2L}{R}$

$$= \frac{RC}{2}$$

Inductance: $L = \frac{R^2C}{4}$

$$= \frac{t_p^2}{C}$$

Resistance: $R = \frac{2t_p}{C}$

Capacitance: $C = \frac{4L}{R^2}$

$$= \frac{2t_p}{R}$$

Charge: $Q = CE$

THE OVER-DAMPED CONDITION: $R > 2\sqrt{\frac{L}{C}}$

Current: $i = \frac{E\mathcal{E}^{\left(\frac{-Rt}{2L}\right)}}{NL}\sinh Nt$

where $N = \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$

Voltage: $e_C = E\mathcal{E}^{\left(\frac{-Rt}{2L}\right)}\left(\cosh Nt - \frac{1}{N}\sinh Nt\right)$

Time of Current Maximum: $t_p = \frac{1}{N}\tanh^{-1}\frac{2NL}{R}$

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